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METEOROLOGICAL OBSERVATIONS ABOVE 30 KILOMETERS

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METEOROLOGICAL OBSERVATIONS ABOVE 30 KILOMETERS

A part of the proceedings of the Conference on Meteorological Support for Aerospace Testing and Operation, held at Colorado State University, July 11-12, 1963

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FOREWORD

The American Institute of Aeronautics and Astronautics and the American Meteorological Society jointly presented a program on Meteorological Support for Aerospace Testing and Operation at Colorado State University, Fort Collins, Colorado, July 11–12, 1963.

The intent of these meetings was to present the status and outlook for information on the structure of the atmosphere, especially at high levels; on the theory and observation of high atmospheric behavior; and on related topics. Thus the aerospace engineer would be given a picture of the information available from the atmospheric sciences as input to the design and operation of aerospace systems and the future prospects for more comprehensive information. The three papers presented here comprised the session on Meteorological Observations Above 100,000 Feet. Together they are a comprehensive survey, status report, and outlook for the field of meteorological sounding rockets. The subject is discussed from both an engineering and applications viewpoint because of the multidisciplinary interest in this topic.

The atmosphere above 30 km (100,000 ft) is becoming recognized as an important region by the meteorologist, other atmospheric scientists, and the engineers who must design the vehicles which will traverse or operate in this area. Requirements are being expressed continually by military, civilian, and scientific organizations for more complete and comprehensive knowledge of the structure and behavior of this region and of its relation to the rest of the atmosphere. This zone, which by weight, contains only a small percentage of the atmosphere, was once assumed to be rather static and uninteresting, but the mteorological sounding rocket observations have shown the reverse. It has been revealed as a dynamic region which is subject, in the winter season for example, to dramatic changes in the circulation patterns accompanied by rapid changes in temperature which can amount to 50° C or more within a few days.

This important region presents a challenge to the engineer and meteorologist. It represents a challenge to the engineer to devise suitable observational vehicles and techniques required for the exploration of this region—and, of course, it represents a challenge to the meteorologist to analyze these observations and present a consistent description and explanation of this region to be of use, among others, to the engineer who must design and develop vehicles that traverse this region. Thus, this session was organized as a joint session of two societies in order to transfer meteorological information to the engineers and engineering information to the meteorologists. These three papers do just this: they survey the present status of meteorological rocket observations from both an engineering and a meteorological view and offer a basis for looking to the future.

The first presentation by Mr. Masterson discuses the small solid propellant sounding rocket systems which have been used to measure the atmospheric structure from 30–60 km (~ 100,000–200,000 ft) and have provided a wealth of information about the upper stratosphere and the lower mesosphere. These systems are examined with respect to the vehicle, the sensors, and data retrieval. The problems of the location of the meteorological stations are reviewed and, with the state-of-the-art in mind, the future rocket systems are explored.

The second paper by Dr. Teweles is a comprehensive survey of the meteorology of the 30- to 60-km (1000,000- to 200,000-feet) region based on the sounding rocket observations. The structure of this atmospheric region is discussed along with the characteristics of the circulation which are illustrated with synoptic analyses. These synoptic analyses vividly portray the great changes that take place from one season to another and within a season, they also accentuate the need for system improvement and greater observational coverage.

The last paper of the session by Dr. Nordberg carries the discussion to the vicinity of 90 km (300,000 ft) covering the engineering and meteorological aspects of the sounding rocket observations which employ the two-stage solid propellant rocket systems. These observations are based on the sodium vapor, the acoustic grenade, the falling sphere, and the pitot-static tube experiments which were introduced and performed successfully for the International Geophysical Year. The results of these experiments and the physical characteristics of the mesosphere are discussed in his paper.

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THE STRATO-MESOSPHERIC METEOROLOGICAL ROCKET

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CONTENTS

THE STRATO-MESOSPHERIC METEOROLOGICAL ROCKET

John E. Masterson*

INTRODUCTION

Today's understanding of the structure and state of the atmosphere surrounding the earth is the result of major developments in synoptic meteorology. All major developments in this science have been based on breakthroughs in observational techniques or on discoveries attending observation. On sailing ships, seamen observed the doldrums, the tradewinds, and the roaring forties, and recorded these vagaries of the weather in their logs. From use and analysis of these records, the art of navigation was refined and developed into a science.

Similarly, when the speed of communication was increased by the invention of the telegraph, the synoptic meteorological network, a new development, came into existence. Almost a century ago, this network of observation and communication stations gave to the weatherman his first two-dimensional picture of cold fronts as they moved across the country.

In the early 1900's kites and balloons were used, to sound the atmosphere and to observe the upper winds. Once again, an improved observational technique made possible a better understanding of the earth's atmosphere. This time the third dimension was added.

Today, a half century later, a weather observation platform circles the earth, observes the clouds, and transmits pictures to ground stations, thus producing an elaborate portrait of weather systems and revealing a startling organization in what had appeared to be disorganization. Once again, a new observational technique has led to a greater understanding of the atmosphere but also to many questions and problems concerning the general circulation.

In a similar manner, the meteorological rocket has produced *in situ* observations of the top 1% of the atmosphere, heretofore inaccessible. This region cannot be reached from beneath by sounding balloons nor sampled by satellites from above, but can be measured for meteorological purposes only by instruments borne by or ejected from self-propelled vehicles.

The data produced by this small, solid-propellant rocket have not only verified and supplemented the sparse observations of larger rockets such as the Aerobee, the Nike-Apache, and the Nike-Cajun, but have provided direct observation of exciting phenomena such the reversals of the stratospheric westerlies and easterlies in the spring and fall. 23870

In surveying the strato-mesospheric meteorological rocket, this paper describes the volume of the atmosphere in which meteorological observations are being made with the rocket, the meteorological parameters measured, the vehicles and sensors used, and some methods of data retrieval. The current developments of components of the meteorological rocket system are discussed. The sampling of the atmosphere and the use of the meteorological rocket as a photographic platform are described briefly. Augmentation of the meteorological rocket network is discussed, and finally, the next generation of the meteorological rocket is examined. author

In a survey such as this, much of the material must be gathered from a variety of sources, each of which makes a unique contribution to the overall picture. The assistance of the many whose contributions are noted by reference or discussion is gratefully acknowledged.

*The opinions expressed in this paper are those of the author and are not necessarily those of the Department of the Navy.

VOLUME OF ATMOSPHERE EXPLORED

The volume of the upper stratosphere and the mesosphere explored by the present meteorological rocket extends from approximately 30 to 60 km above mean sea level. The maximum altitude range of 60 km was arbitrarily arrived at by doubling the altitude capability of the first meteorological rocket vehicles, the Deacon and the Loki I. Nature, however, has not designed this volume of the atmosphere to conform conveniently to man's ability to observe or understand it.

The familiar temperature structure of the first 100 kilometers of the earth's atmosphere is shown in figure 1. This figure shows that with increasing altitude the well-measured troposphere, the temperature decreases about 0° K. Thence, after an isothermal layer approximately 10 kilometers thick, at least in the mid-latitudes, the temperature increases approximately 55 deg in the next 25 to 28 km. The temperature at the stratopause, at an altitude of about 45 to 47 km, is about 270° K or almost 0° C. Beyond another isothermal stratum 5 km thick, the temperature decreases with increasing altitude through the mesosphere. The stratum through which this temperature decrease exists is 30 to 32 km thick. At the mesopause, at approximately 80 km, a second temperature minimum of 180° K is reached. Beyond this third isothermal layer, approximately 10 km thick, the temperature begins its increase in the thermosphere at an altitude of approximately 90 km. The characteristics and behavior of the ionosphere, in contrast to those of the unmeasured mesosphere, are well known from a worldwide network of indirect ionospheric sounding stations and by extensive studies of radio propogation.

Little is known about this strato-mesospheric volume of the atmosphere with which we are concerned. The misnamed stratosphere is not always a region of stratified flow, but experiences turbulence, reversing and shifting winds, and a varying temperature profile. There is in midwinter the dramatic breakdown of the polar low vortex. On these occasions the 75-m/sec (150-knot) winter mid-latitude westerly winds suddenly reverse and become 50-m/sec (100-knot) easterly winds. Finger, Teweles, and Mason (ref. 1) show that stratospheric disturbances or discontinuities develop at higher levels and penetrate downward to become influences in the troposphere. It is within this strato-mesospheric volume of the atmosphere that density (and its variation) becomes an important parameter to objects entering

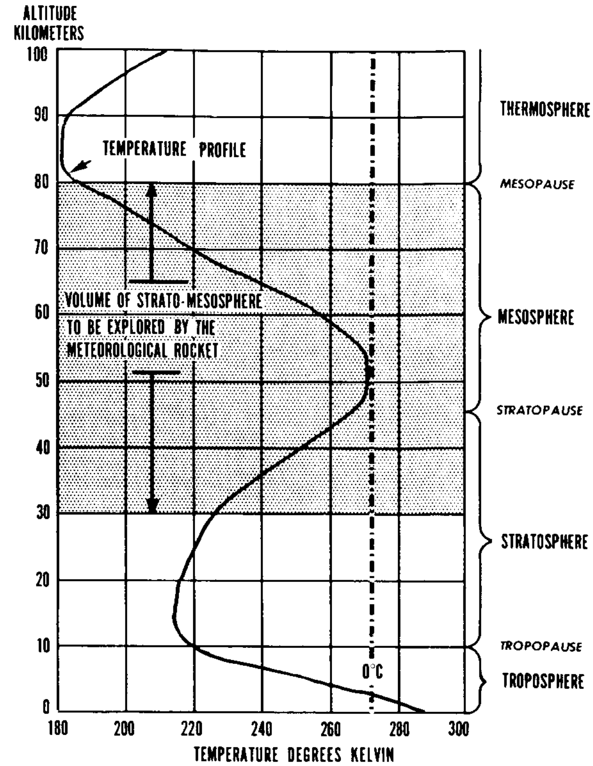

Figure 1.—Temperature profile of *the first 100 kilometers* of the earth's atmosphere. (Taken from the U.S. Standard Atmosphere 1962.)

the earth's atmosphere from space. It is in this region that meteors succumb to erosion by the atmosphere. The slower moving (10 km/sec) meteors first become visible at altitudes between 80 and 90 km, and disappear between 50 to 60 km (ref. 2). The volume of the atmosphere between 30 and 80 km is truly the "interface of space," yet our lack of knowledge concerning it is such that it has led to its being commonly called the "igno-sphere."

THE ROCKET VEHICLE

The meteorological rockets which are used at the stations of the national Meteorological Rocket Network (MRN) are small solid-propellant rockets that can be conveniently handled by two or three men. The launchers are simple and can be loaded, elevated, and directed in azimuth by hand. The two types of rocket systems are used. In the Loki which was adapted from a tactical weapon system, the booster or motor completes its burning and drops off, and the instrumented payload dart is propelled into the atmosphere on a ballistic trajectory. In the second system, the rocket motor remains with the payload until apogee, or until the payload has been ejected for its intended mission. Examples of the latter system are the Deacon and the ARCAS rockets. Webb (ref. 3) has carefully reviewed the history and development of the meteorological rockets Loki and ARCAS.

There are essentially three meteorological rocket motors that are used in various combinations and with numerous adaptations to form the backbone of the systems which sound the atmosphere for the meteorologist. These rocket motors are the Deacon, the Loki and the ARCAS. Data on the relative size and performance of these meteorological rocket vehicles are shown in figure 2.

It is worthwhile to review the Deacon rocket, which started its career as a single-stage rocket, but has been more useful in recent years as a booster (first stage) or as the sustainer (second stage) of various rocket combinations.

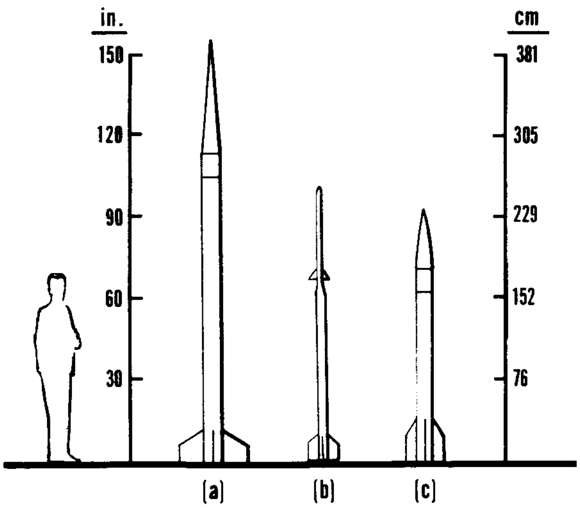

Figure 2.—The meteorological rocket vehicles: Deacon (a), Loki (b) and ARCAS (c).

	(a)	(b)	(c)
*Length, cm	391	262	234
in.	154	103	92
Diameter, cm	16.5	7.61	11.4
in.	6½	3	4.5
Weight			
Motor, kg	70	10.4	30
lb	155	23	66
Gross, kg	20	4.1	5.4
lb	45	9	12
Altitude, km	30	60	60

*Motor + Payload

The Deacon rocket motor originated in 1946 under the auspices of the National Defense Research Council as one of a family of rocket-motor research designs humorously named in inverse order of size after ecclesiastical dignitaries (ref. 4). In 1948, under sponsorship of the U.S. Navy Bureau of Aeronautics, the Bendix Research Laboratories undertook the development of a meteorological rocketsonde system using the Deacon rocket motor. This motor, which was used as the propelling force in this single-stage vehicle, has also been used as a booster or as a sustainer in two-stage rocket vehicles such as the Deacon-Arrow and Nike-Deacon. The Arrow is another version of the Loki motor.

The Deacon rocketsonde was designed to provide telemetered and radar-derived data of time, altitude, temperature, pressure, wind speed and wind direction from an altitude of approximately 30 km. Wind and temperature data (figure 3) were obtained from a Deacon rocketsonde flight on April 11, 1951 (ref. 5). Although the altitude reached on this flight was

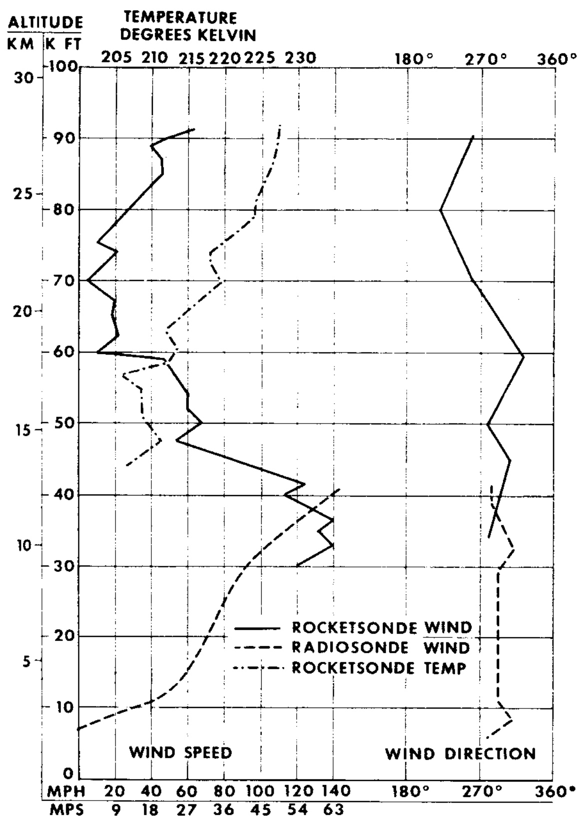

Figure 3.—April 1951 Deacon rocketsonde and concurrent radiosonde data.

only about 28 km (92,000 ft), it compares favorably with the altitude of 12 to 15 km attained by the typical balloon-borne radiosonde coincident with this flight on that date in 1951.

The Deacon rocket, which carried a gross payload of 20 kg (45 lb) to more than 27 km above mean sea level, had a total weight of more than 93 kg (205 lb). The vehicle diameter was approximately 16.5 cm (6½ inches) and the over-all length was 395 cm (155 inches). There were four square fins which had an area of about 412 square cm (64 square inches) per fin. The motor developed a thrust of 2700 kg (6000 lb) for 3.3 sec, and the burnout speed was about 1200 m/sec (4000 ft/sec). At the apogee of the rocket trajectory, the payload instrumentation was ejected and a baseball-type parachute 7.3 m (24 ft) in diameter deployed and carried the instrument package to the ground. The descent rate after deployment of the parachute was about 20 m/sec (50-60 ft/sec). This work extended from April 1948 to mid-1951 (ref. 5).

The Loki rocket was named after a god of Norse mythology who was the god of mischief, conceit, and devilishness. Those who have worked intimately with its adaption as a weather rocket must feel that it inherited the characteristics of its namesake. The Loki rocket was originally designed as an anti-aircraft weapon prior to the Nike anti-aircraft system. The basic Loki system was developed by the Jet Propulsion Laboratory (JPL) for the U.S. Army Ordnance Corps. It was first adapted as a meteorological rocket by the Office of Naval Research (ONR) to provide rapid wind measurements for the Atomic Energy Commission (AEC) tests in the Pacific. The first models of the Loki adapted for meteorological purposes, the wind atmospheric sounding projectile (WASP), were fired from the destroyers *Kyes* (DD 787) and the *USS Shelton* (DD 790) on February 7, 1956 in the Long Beach operating area (ref. 6). Reflective chaff was ejected at approximately 30 km and was tracked by the Mark 25 radar of the ship's gunfire-control system. The Loki system was used operationally during the AEC operation Redwing in the spring of 1956. A series of Loki firings was made by ONR in June 1956 at the White Sands Proving Ground in which a 1.2-m metalized Mylar parachute was ejected from the Loki dart.

The Loki motors and darts designed and built by the JPL have been further developed to yield a dependable and efficient atmospheric sounding rocket. There are now three versions of the Loki with improved propellant and an efficient separation of the booster and the dart. They are the HASP, the ROKSONDE, and the JUDI. The high altitude sounding projectile (HASP) is the shipboard successor to the WASP. It has been modified and qualified for use aboard U.S. Naval ships by the Naval Ordnance Laboratory, White Oak, Maryland. The Marquardt Corporation's version of the Loki is named the ROKSONDE. A large number of operational chaff rounds have been flown. The latest development of the Loki rocket system, an improved version which uses a high performance motor, is called the JUDI, and was developed by Rocket Power, Incorporated, (RPI) of Mesa, Arizona.

These first versions of the Loki used chaff as radar-tracked payloads for measuring winds. Since then inflated spheres and parachutes have been successfully ejected from the Loki dart configurations of the HASP, ROKSONDE, and JUDI. Now under development are instrumented payloads using the meteorological assigned frequency of either 403 Mc or 1680 Mc for transmitting the measurement of temperature and/or pressure with the Loki-type dart.

The next addition to the Loki system will be the ranging capability of the 403/1680-Mc transponder which has been demonstrated in the AN/DMQ series of ARCAS rocket flights.

The Loki meteorological rocket system has produced valuable information on the circulation of the atmosphere in the region between 30 and 70 km. The chaff targets have been improved and have produced much more data than that yielded in 1956 by the first soundings which were only 3 to 4 km in depth. At present, routine soundings with copper or nylon chaff provide a radar track which yields very acceptable wind data. The Loki system is easily handled and has a high degree of reliability. The comparatively small payload volume is its primary drawback.

The ARCAS, was sponsored as a meteorological rocket in 1958 by ONR; its development has also been supported by the Air Force Cambridge Research Laboratory. Because the ARCAS is an end-burning rocket, it has a lower acceleration rate than the Loki and its predecessor, the Deacon, which are internal-burning motors. The maximum acceleration that the payload of the ARCAS is subjected to at launch is less than 60 g. This permits standard instrumentation such as the radiosonde cavity to be flown in the rocket without being subjected to high acceleration.

However, this slow take-off velocity (long-burning 28 sec) has the disadvantage of making the ARCAS rocket sensitive to cocking into the wind during the initial stages of the launch, thereby increasing its impact dispersion. Nevertheless, the ARCAS has a record of more than 1,800 flights, from which much information has been obtained about wind and temperature in the region between 30 and 55 km. The ARCAS has also proved to be useful in checking out development sensors and rocket payload instrumentation.

The Deacon and a Loki II configuration have been combined into a successful two-stage meteorological rocket, the Deacon-Arrow, which has been used for special programs requiring the measurement of winds in the mesosphere. This combination served as a carrier for a payload of Mylar chaff tracked after ejection by radar between 85 and 55 km. This rocket system, described by Force (ref. 7), has a record of reliability greater than 90%; Smith (ref. 8) also reported a high degree of operational success with this basic rocket combination for measuring winds in the mesosphere. There are current development efforts toward boosting both the Loki type rocket and the ARCAS with their respective payloads into the 80- to 100-km region. There are also other promising meteorological rockets both on paper and in research and development testing, such as the Raven of RPI and the ROKSONDE 200 of Marquardt Corporation but they are not ready for review at this time.

There are two significant areas of development on the meteorological rocket vehicle which will enhance the usefulness of the small, solid-propellant rocket as a tool for mesospheric sounding.

In order that the meteorological rocket may be launched from geographical areas other than missile ranges and to provide a desirable distribution of observational network stations, it is necessary that the flight hardware be nonhazardous after its task is completed. This applies, for example, to the empty motor case, the fins, and the nozzle. To this end, there are programs in which frangible/consumable hardware are being developed. The feasibility of the frangible rocket motor case has been demonstrated.

A second significant and promising development now being applied to the meteorological rockets is the combining of the booster and the sustainer motors into one rocket motor case. This *dual-thrust* or *thrust-modulated* concept which is not a new one, will result in an accelerated takeoff, with a consequence of decrease in the impact dispersion. In addition, the inter-stage hardware plus one motor case and one set of fins will be eliminated. Neither of these developments will come easily. They will require a large amount of well planned engineering effort as well as support from the meteorological rocket users.

SENSORS AND INSTRUMENTATION

The second integral part of a meteorological-rocket observational system consists of sensors and instrumentation, including the devices for measuring meteorological parameters *in situ,* and the instrumentation for relaying the acquired information to the ground.

There are five meteorological parameters which can now be measured in the volume of the atmosphere between 30 to 70 km. Table I lists these parameters, the basic sensors, and the associated flight and ground instrumentation. Also included is water vapor, a parameter for which there is no operational sensor available for a meteorological rocket, although the aluminum oxide sensor appears promising.

The two basic techniques for measuring meteorological parameters in the atmosphere are the passive and the active. In the passive technique radar is used to track the movement of a target through the atmosphere. The velocity of the wind can be derived directly, and the density of the atmosphere may be computed by considering the drag coefficients of the target. In the active technique, such meteorological parameters as temperature, ozone, and pressure are measured *in situ* by a sensing element, and the data are telemetered to a ground station and recorded. Winds and density may be measured by the active technique with a transponder carried by a descending parachute or an inflated sphere.

In a comprehensive review of meteorological rocket instrumentation, Leviton (ref. 9) discussed primary meteorological rocket instrumentation as well as current developments in sensors and instrumentation.

Atmospheric motion, or wind, was the first parameter measured with the present meteorological rocket vehicles as carriers for chaff or dipoles which were released and tracked by radar to provide a measurement of horizontal winds. Some of the first experiments were referenced in the preceding section. Although the chaff cloud is not a truly discrete

TABLE I.—*Sensors and Instrumentation Used in Measuring Various Atmospheric Parameters by Meteorological Rockets*

Parameter	Altitude, km	Sensor	Instrumentation	
			Flight	Ground
Wind	30–75	Target— chaff, parachute, sphere	Rocketsonde	Radar Radar GMD Radar GMD
Temperature	30–60	Resistor— bead rod film	Rocketsonde	GMD
Density	30–100	Aerodynamic inflated sphere gage	Rocketsonde Rocket probe	Radar Modified GMD–2
Pressure	30–60	Hypsometer	Rocketsonde	GMD
Ozone	20–60	Chemiluminescent optical	Rocketsonde	GMD
Water vapor	20–60	Sensor under development	Rocketsonde	GMD

target when compared with a metalized parachute or an inflated radar reflective sphere, chaff has now been so improved that reliable wind data may be obtained throughout a stratum extending from 80 to less than 30 km. This, however, is accomplished by multiple releases of the chaff.

The wind-sensing parachute was the logical successor of chaff. The metalized parachute has been developed to eject and display from the meteorological rocket at maximum altitude without the use of mechanical deployment such as inflated tubing or springs. The apparent top altitude at which parachutes can be deployed without a complicating mechanism is about 70 km; however, their stability for wind determination at this altitude has been questioned. At Langley Research Center, National Aeronautics and Space Administration, H. Murrow and others are investigating the behavior of the rocket-ejected parachute. The average effective maximum altitude for the 4.5-m parachute, deployed from the ARCAS rocket, appears to be 55–60 km. Parachutes have also been successfully deployed from the dart of the Loki system. Winds derived from the track of the rocket-ejected metalized parachute have provided a large number of the rocket wind measurements made from 55–30 km.

The ROBIN (rocket balloon instrument) is an inflated Mylar sphere with an internal corner radar reflector, ejected from an ARCAS rocket, to measure atmosphericv density, with the measurement of winds as an important by-product (ref. 10). The wind data may be obtained from the radar plot board or by computer reduction of the radar data.

The current measurement of temperature in the statosphere and the mesosphere is an extension of the technique using the basic AN/AMT–4 radiosonde with the balloon-borne bead or rod thermistor. A number of groups associated with missile range meteorology have worked extensively on the calibration, the mounting, and the exposure of the rocketsonde thermistor, and the temperature measurements which are now being made in the stratosphere show a marked improvement over the first measurements made in 1960. There are a number of problems in using bead thermistors; the most important of which is due to radiation. Refining the mounting and engineering of the thermistor may increase to about 70 km the maximum altitude at which the resistance technique can effectively measure atmospheric temperature. The application of thin films as temperature sensors is being explored and appears promising, while the acoustic transducer is another temperature sensor on which encouraging research is being conducted for rocketsonde applications.

The aerodynamic method of measuring density—that is, measuring the drag on a falling sphere—has been used with both radar and acceleration-measuring instrumentation in the sphere. One of the first spheres which used a DOVAP system within a 4-ft-diameter inflated nylon sphere was described by Bartman et al. (ref. 11). An accelerometer within a solid sphere has provided good density measurements (ref. 12). However, the ground and flight instrumentation in both cases are considered too sophisticated for use on a synoptic meteorological basis. The less complex ROBIN system has produced a significant amount of synoptic data of both density and winds, and there have been almost 500 flights of ARCAS-ROBIN alone, of which approximately 300 were operational. However, as pointed out by Leviton (ref. 9), an FPS–16 radar and a large computer are necessary for the use of this density measurement technique.

Density values may be computed from the rocketsonde measurement of temperature in the stratosphere by the use of the temperature/height relationship. Thiele (ref. 13) has refined this technique for data reduction by the use of a small meteorological computer such as the G–15 type.

To provide density data at sites where there are no large radars, it is necessary to investigate a measuring technique whereby the data may be received by standard meteorological telemetry, i.e., 1680 Mc and 403 Mc. Among the proven techniques is one deriving density from the measurement of ram pressure and a knowledge of the velocity and altitude of the rocket vehicle. Thermal conductivity gauges and gas-ionization gauges are among the pressure measuring devices suggested for the meteorological rocket. Ainsworth and LaGow (ref. 14) measured density with a pitot-static tube as the chamber and a diaphragm gauge as the sensor. The carrier vehicle was first the AEROPEE and later the Nike-Cajun. These measurement devices are now being reduced in size for use in a synoptic meteorological rocket system with a pitot-static tube as the chamber and a dia-as the carrier. A modified AN/DMQ-type flight package will provide ranging data and the meteorological pressure-density will be measured by the diaphragm gauge. Modified AN/GMD–2 ground equipment will receive and record the necessary information on magnetic tape during the ascending leg of the rocket trajectory.

The ionization of air molecules by a source of radiation is a phenomenon that is being investigated for the direct measurement of density. The devices used include X-ray and Bremsstrahlung densitometers. The α- and β-forward-scatter technique is also being investigated. Although these methods of measuring density are promising for small rockets, they are not ready for use in the synoptic meteorological system.

The measurement of ozone, refractive index, and water vapor will continue to go through the balloon-borne phase of development until the instrumentation and sensors are proved reliable enough for use in a rocketsonde.

DATA RETRIEVAL

The retrieval of data is the third integral part of the meteorological rocket observational system. The vehicle may function both as a sensor and as a platform for other measuring devices. Meteorological data are retrieved by the passive technique using ground radar tracking, or by the active technique using the rocket-borne telemetry system.

An advantage of the passive technique of measuring the atmosphere is that the more expensive and complicated portion of the system—the AN/FPS–16 radar—remains safely on the ground, while an inexpensive inflated metalized sphere comprises the flight instrumentation. The active technique, on the other hand, requires that the data be telemetered from the point of observation to the ground station. Thus the airborne components—platform, sensors, and telemetry—must be considerably more complicated and expensive than the sphere, parachute, or chaff in the passive method. However, as the active technique of observing and gathering the measurements from the strato-mesosphere becomes more widely used, the sensors and telemetry will decrease in cost, and their reliability and accuracy will increase.

As mentioned in a previous section, there is under study and development a modification of the AN/GMD–2 for use as a tracking and data-receiving unit for meteorological rockets which would sense the atmosphere on the ascending leg of their trajectory. Modification of both the in-flight package and the ground-based ilnstrumentation will be necessary. Modulation techniques are being developed to obtain accurate ranging data from which the velocity and position of the rocket will be derived as well as information from its sensing payload on the ascending trajectory.

The meteorological data computer will be an integral part of the data-retrieval system. The computer may be either the large multi-use computer which performs the meteorological workload along with other computing functions, or it may be the small meteorological computer which is being used with increasing frequency at major meteorological observing stations. Automatic data retrieval from the meteorological rocket will follow the automation of the retrieval of data from the balloon-borne rawindsonde.

SAMPLING AND TELEVISION FROM ROCKETS

The image of the meteorological rocket has been primarily that of the rocketsonde and the rocket probe to provide measurements of wind, temperature, and density. However, the larger rockets have demonstrated their ability to provide other types of data as well, such as atmospheric sampling and television from high altitudes when required for special events or projects.

Actual samples of the atmosphere from the stratosphere and the mesosphere were brought back even before the IGY. One of the first programs of sampling or collecting particles from the atmosphere for subsequent analyses was initiated by the University of Michigan in 1947 and carried on for nine years. During this time, about 70 air sampling bottles were flown on various types of rockets, and samples were collected at altitudes ranging from 40 to 100 km and parachuted to earth (ref. 15). While this technique is not recommended for synoptic meteorology, it is conceivable that the meteorologist will be called upon to provide air samples from the strato-mesosphere.

Although the meteorological satellite will provide increasingly complete photographic coverage, the tactical meteorologist will be called upon to provide photographs of the clouds affecting the weather in his immediate area of responsibility. The meteorological rocket will provide the platform for a television camera to transmit such cloud pictures over areas from which the meteorologist currently receives no data.

Some of the first cloud photographs obtained by rockets were produced by a Viking rocket flown from White Sands. The most striking and historic photograph was that series of frames comprising the "Rocket Portrait of a Tropical Storm," by Hubert and Berg (ref. 16), which showed the circulation of a low pressure area over Brownsville, Texas. This rocket photography of weather as depicted by clouds was paralleled in an effort which attempted to photograph hurricanes as they moved along the east coast of the United States, With the development and improvement of the television camera and ground-receiving equipment, the meteorological rocket will provide local-weather reconnaissance not available from the meteorological satellite. Because of their limited payload size and altitude capability, the Loki and the ARCAS as single-stage vehicles are not contemplated for this task. It will be a mission for improved meteorological rockets.

THE METEOROLOGICAL ROCKET NETWORK

There is in existence today an active meteorological rocket network which has been described by the MRN Committee of the Inter-Range Meteorological Working Group (ref. 17). The product of this group of six to ten stations is represented by approximately 2,000 soundings of wind between 30 and 55 km. There have been about 200 soundings which produced temperature measurements between 30 and 50 km. From the sequences of these measurements, the dramatic spring and autumn wind reversals have been witnessed and the January breakdown of the polar low vortex has been documented. These are examples of stratospheric events recorded by the MRN. The network, however, has served to point out one of its own great deficiencies—the need for synoptic data to be produced on an orderly basis.

There are three significant areas in which the productivity of the meteorological rocket network may be increased and be made more effective. The development of the frangible/consumable rocket (motor and/or dart) is necessary before the existing network can be expanded to provide synoptic coverage adequate for a complete analysis of the stratosphere and the mesosphere. The increasing number of rocketsondes from the ocean areas by ships which have fire-control radar and the ability to launch small meteorological rockets such as the HASP, will augment data obtained by the permanent land stations. The implementation of a number of foreign rocket-launching sites during the International Year of the Quiet Sun (IQSY), as recommended by COSPAR, will produce the first data from which maps of the northern hemisphere may be constructed. Until a truly synoptic meteorological rocket network is realized, the analyses of data from the existing stations will be incomplete, although still most promising.

THE ROCKET OF THE FUTURE

The background, the status, and the current development of the meteorological rocket and its sensors have been presented. Some of the aspects of data retrieval have been explored. Based on this review, the future generation of meteorological rockets may be projected. In view of the fast-moving state of the art, the next two to four years is considered "future."

The basic parameters to be measured are winds, temperature, and density with water vapor, ozone, pressure, cloud cover, and particulate matter certainly of interest and their measurement due to follow as their sensors are developed. As the exploratory rocketsonde flights measuring ozone prove to be of significant interest and value, ozone will be the next parameter that will be measured on a synoptic basis. The region between 30 and 60 km will continue to be of primary interest for synoptic soundings. However, with the increase in vehicle capability there will be an increase in the number of measurements of winds and density made between 60 and 80 km but on a less intense time scale than the current soundings to 60 km.

Unless there are significant developments in the chemistry of solid propellants that would be applicable to the meteorological rocket, the most promising areas of improvement are the frangible/consumable rockets, as previously noted. Use of the frangible/consumable rocket will increase the number of sites from which meteorological rockets can be launched. Where the frangible/consumable rocket is not used, the dual-thrust capability will decrease the impact dispersion of the booster case and will be less expensive than two-stage vehicles.

The next generation of the meteorological rocket will sense the atmosphere by techniques that are now known and understood. Hardware for the sensors and instrumentation are now in the laboratory or are being flown on balloons. There will be improvement in the exposure of the sensors as well as their coupling to the transponder instrumentation.

A physical change will occur in the instrumentation package, which is now on its way to microminiaturization. The black box will be replaced by two dimensional electronics or thin film circuitry—literally a black sheet. The full capability of the GMD will be realized, and it will provide the ground equipment around which the automated data-retrieval system will be built.

The thermistor temperature element, with a large negative temperature coefficient of resistance, will continue as the principal means of sensing temperature. However, the form of the bead thermistor may change to provide greater sensitivity. Acoustic transducers are under development for use as atmospheric temperature-measurement devices and may replace thermistors for this purpose.

The aerodynamic method of measuring density by tracking an inflated falling sphere will produce density data from above 100 km and will continue to be used at meteorological rocket sites, especially where accurate tracking radars are available. This is in accord with the principle of using the system which flies the less expensive instrumentation and keeps the expensive tracking, receiving, and recording equipment on the ground. Where no tracking radars are available, the accelerometer technique may be developed sufficiently to be applied to a small meteorological rocket (ref. 18).

The direct measurement of density will be by *gauge densitometers* utilizing the scatter or attenuation phenomenon of nuclear radiation. These measurements will be made on the ascending leg of the rocket trajectory.

In 1958 Haig and Lally (ref. 19) proposed the global horizontal sounding technique (GHOST) and suggested that a super-pressurized balloon be instrumented with microminiaturized thin film electronics as external instrument packages. An instrumented inflated sphere is now feasible as a result of progress in thin-film development and microminiaturization during the past five years. The injection and inflation technique has been demonstrated with current meteorological rockets. By applying the instrumented inflated sphere concept to a vertical observational sounding technique, winds and temperature data may be obtained from the rocket-ejected sphere. R. G. Moore at Thiokol Chemical Corporation, Ogden, Utah, in 1963 wrote that he had completed engineering studies on this concept utilizing thin-film and integrated-circuit manufacturing techniques and suggested further engineering refinements in solid-state telemeter transponders.

The proposed meteorological rocket system will be a dual-thrust single-stage rocket which, on the ascending leg of its trajectory, will measure atmospheric density and telemeter the resulting data, including ranging, to a modified AN/GMD–2. Upon approaching apogee, an instrumented inflated sphere will be deployed and the frangible/consumable rocket, having completed its task will destroy itself. As a platform for sensors and the telemetry-transponder instrumentation, the sphere will fulfill its mission as it descends to 30 km or lower. The temperature and wind data will be retrieved through the AN/GMD–2. Figure 4 illustrates this concept.

In the development of this system the first vehicle used may be the booster-dart combination. By disposing of the booster in a safe fallout zone, only the dart will remain to be destroyed after its task is completed. For this purpose, a natural trigger may be the higher temperature of the dart when it reaches apogee and starts to enter the atmosphere than when it was launched. In addition, the first models of the instrumented sphere may have their electronics as external packages as was suggested by Haig and Lally for the horizontal sounding balloon.

In summary, the meteorological rocket is the tool by which that interesting volume of the earth's atmosphere between 30 and 80 km will be measured and explored. From these data will come greater understanding of the meteorological processes and relationships in the stratosphere and the mesosphere.

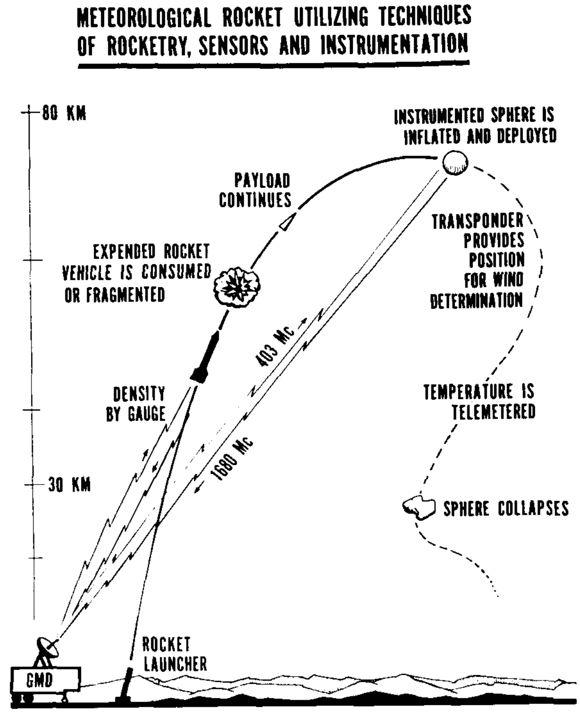

Figure 4.—The proposed strato-mesospheric meteorological rocket system. Known concepts, with techniques now under development, will be used as the frangible/consumable vehicle, the ejection of an inflated sphere with microminiaturized instrumentation, and sensor packages with integrated or thin-film circuitry.

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APPLICATION OF METEOROLOGICAL ROCKET NETWORK DATA

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CONTENTS

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Sidney Teweles

INTRODUCTION

With the formation of the Meteorological Rocket Network (MRN) in 1959, the capability for synoptic analysis rose to twice the height possible with the existing rawinsonde network. Less than three years earlier, as a part of the IGY program, an equally significant upward extension of the hemispheric rawinsonde network was achieved through the application of greatly improved balloons, instruments, and tracking techniques. The hemispheric charts up to the 10-mb or 31-km level that could be constructed with the new rawinsonde data have since provided a firm foundation for use in the analysis of higher level charts based on rocketsonde information.

The development of the comparatively inexpensive meteorological rocket, carrying a payload weighing several kilograms to heights of 60 or 70 km, was mainly responsible for the inception of the MRN. In the few years of the MRN's existence, a host of new and improved sensors has been devised. From time to time, additional launching sites have been adapted for use as MRN stations. Throughout the period, the number of observations increased remarkably and, beginning with July 1962, the monthly total occasionally exceeded one hundred.

CLIMATOLOGICAL APPLICATIONS OF MRN DATA

The most important single use of the meteorological rocket has been immediate launching-site support for major missile firings. As one convenient way of reporting results from a particular site, observations made in direct support of firings may be combined into time-height cross sections along with other observations made for developmental and other network purposes. For some of the launching sites, substantial effort has already been expended toward establishing a climatology of the wind in the vertical over that point of the earth. Such studies generally include seasonal or monthly mean profiles. The frequency of occurrence of excessive vertical wind shear has also been determined. In a few cases there have been studies of persistence or, conversely, the maximum rate of change of wind at a given level.

Vertical profiles of temperature and density for individual launching sites have also been the subject of statistical analysis. At the present time, a major effort in this direction is the preparation of reference atmospheres for each site.

From a meteorological standpoint, true *network* applications are those in which statistics pertaining to two or more stations are integrated into vertical cross sections or horizontal maps. The fact that so many applications of MRN observations have already been made is largely due to the prompt publication of the MRN data report series through a program coordinated by Willis L. Webb (ref. 1).

One of the most important applications of network data is that which is now being made by the U.S. Committee on Extension of the Standard Atmosphere (COESA) in the establishment of a series of supplemental atmospheres at 15° latitude intervals from pole to equator (ref. 2). As basic information for this purpose, all available temperature data have been assembled from radiosondes for the layer below 30 km, from MRN soundings for the layer from 30 to 50 km, and from rocket grenade firings for the higher layer up to the 90-km level. A variety of data from Russia, Japan, Australia, and other countries has also been collected. Reports for each season have been considered separately in order to establish both winter and summer atmospheres.

Since not all latitudes are covered by network stations, the supplemental atmospheres are based on a temperature cross section (fig. 1) constructed by horizontal interpolation and extrapolation of isotherms. This procedure is facilitated by information obtained by processing wind information through the thermal wind equation, which relates the vertical wind shear to the horizontal temperature gradient. Interpolation between latitudes at which observations are made is also necessary in constructing pole-to-equator vertical cross sections of the mean zonal winds. For such wind sections, there is a reciprocal input of information from the temperature data, for the latter may be applied in the hydrostatic equation to compute pressure-heights.

The resulting horizontal gradients of pressure-height help to establish the acceptable range of wind speeds between stations (fig. 2). Thus, by a sort of synergism, it is possible to arrive at useful values of winds and temperatures in the region between stations.

A convenient method of following the seasonal changes and determining the existence of superimposed transient disturbances in the vicinity of an MRN station is to combine its observations in time-height cross sections. Miers (ref. 3) has presented a number of such sections for White Sands, New Mexico, and Pt. Mugu, California, to show the nature of the wind reversals between winter westerlies and summer easterlies that occur in the transitional months. In the fall of 1962, as shown by the White Sands data in figure 3, the transition from easterlies to westerlies was universally regular, progressing downward in September and October at an average rate of 1 km/day.

In general, the spring transition at southern U.S. stations has been more spasmodic in nature, occurring in one or more surges. Initiation of these reversals takes place at upper levels at higher latitudes and then moves downward and southward, sometimes in a

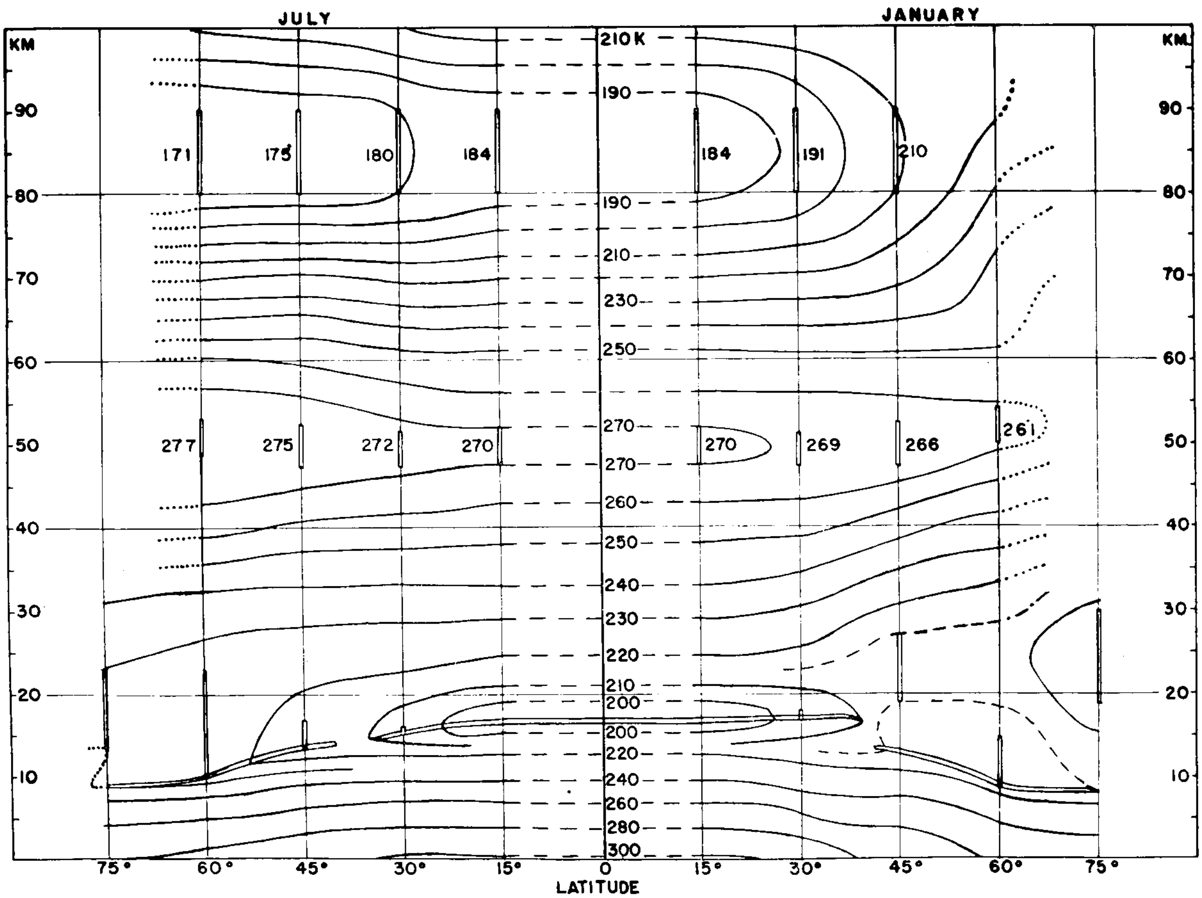


Figure 1.—Proposed latitudinal temperature-height cross section, the basis for supplemental atmospheres at selected latitudes: July (left) and January (right); temperature (in ° K) is shown by isotherms and specifically for each isothermal layer (double verticle lines); tropopause is indicated by double horizontal lines (ref. 2).

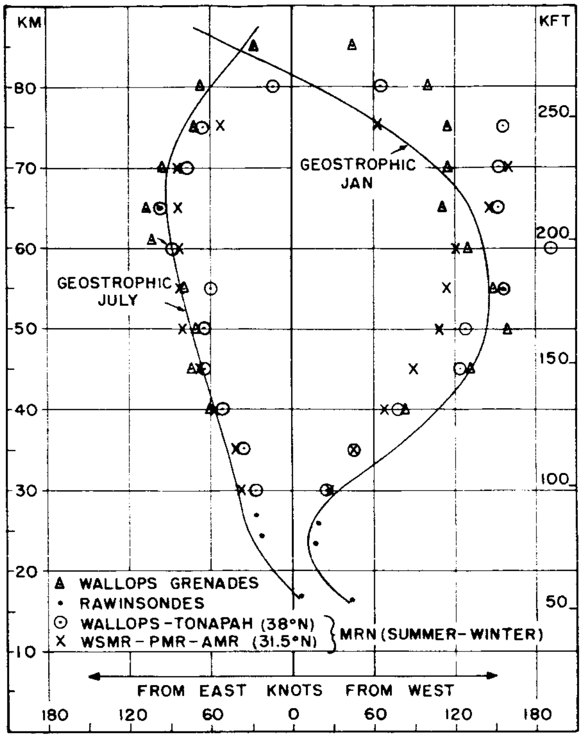


Figure 2.—Zonal wind components. Geostrophic components (solid lines) computed hydrostatically from supplemental atmosphere temperatures at 30° N and 45° N (fig. 1) are compared with zonal components of seasonal average observed winds (coded points) (ref. 2).

matter of a few days. The day-to-day variation in the zonal wind component at Cape Canaveral, Florida, in early 1962 (fig. 4) is fairly representative of the sequence of events to be expected in this season. Strong winter westerlies in February are replaced by easterlies in mid-March, but westerlies reappear sporadically until the summer easterlies take complete control in the latter half of May. The occasional appearance of easterlies in the winter due to high-latitude anticyclogenesis reduces the strength of the seasonal average west winds to a value substantially lower than that often considered typical of winter situations.

Faust (ref. 4) combined the available reports for stations in the latitude zones 21°-38° N (south stations) and 58°-65° N (north stations) to show the annual trend of the zonal component (Fig. 5). At the lower latitude, the *equinoctial* reversals begin earliest in the highest layer and work slowly downward. The changeover is more nearly simultaneous with altitude in the north and is affected much earlier in the season, particularly in mid-stratosphere near 30 km.

In a somewhat different fashion, Appleman (ref. 5) has presented the annual cycle for the southern stations (fig. 6). The standard deviation of the *resultant* wind is also presented to show the much larger variability of the winds in the winter months, notably January. However, the percentage variability remains large in the equinoctial changeover when the absolute variability shows no pronounced minimum even though the monthly mean zonal wind speed passes through zero.

Although temperature measurements have been made with much less frequency than those for wind, some interesting findings have already been presented. Tóth (ref. 6) (fig. 7, left) and Batten (ref. 7) independently found a semi-annual cycle in the temperature above 30 km at stations near 30° N. Tóth remarked upon the similarity of this cycle with the one in the densities at satellite altitudes (fig. 7, right), as presented by Paetzold (ref. 8).

Webb (ref. 9) and others have discussed the great usefulness of combining temperature and wind information in determining the sonic structure of the high atmosphere. In a wintertime situation with strong westerlies (fig. 8), Diamond (ref. 10) shows that an eastward propagating sound wave would encounter a marked vertical increase in sonic speed (defined here as the speed of sound computed from the air temperature added to the velocity of the wind taken positive in the direction of the moving sound wave) and thus be strongly refracted back toward the earth. For this same situation the westward moving wave would encounter a nearly uniform vertical distribution of sonic speed and dissipate its energy toward the thermosphere.

In an effort to measure directly the daily variation of wind velocity, a series of 23 successful rocketsondes was launched on May 9–10, 1961 within a single 24-hour period at Eglin Air Force Base, Florida. The results have been reported by Lenhard (ref. 11) who calculated the phase and amplitude of the diurnal and semidiurnal wind components at several levels.

Through the use of the drag coefficient, the deceleration of the inflatable falling sphere used in this test series provides a means of calculating density, and therefrom temperature, for cases in which the sphere becomes perfectly inflated. Although data reduction is still in the developmental stage, pre-

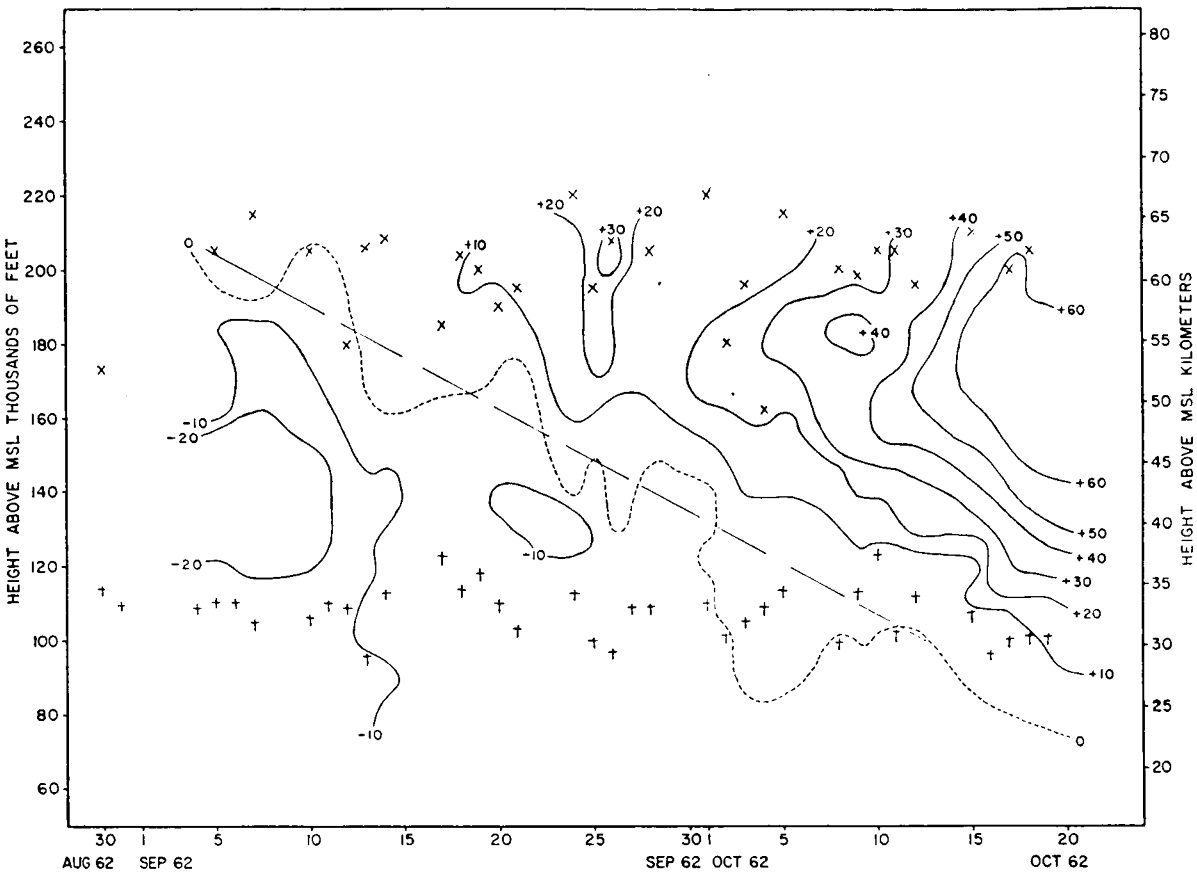


Figure 3.—Zonal wind component, White Sands, New Mexico, August 30 to October 18, 1962; west wind positive, in m/sec. Average downward progression of the autumnal reversal to westerlies is indicated by a straight dashed line. Terminal height of rawinsondes is shown by crosses and of rocketsondes by x's (ref. 3).

liminary results give promise that density can eventually be measured with less than 5% error by this method.

Even with the relatively small amount of data now accumulated, Newell (ref. 12) has been able to make some thought-provoking conclusions with respect to the dynamic climatology of the upper atmosphere. For example, a general northward transport of relative angular momentum by transient eddies has been calculated at a level just below the stratospheric jet stream (at 160,000 feet or 49 km) in winter (fig. 9). In analogy with levels just below the tropospheric jet stream, this northward transport would be accompanied by a similarly directed eddy flux of heat which would explain the relatively small amount of wintertime cooling of the high stratosphere in polar regions. Further calculations indicate that G_Z, the energy generation by meridional differences in heating is sufficient to restore K_Z, the kinetic energy of zonal flow, in about a month and to restore A_Z, the zonal available potential energy in less than four days. Comparative statistics of this sort are essential to a basic understanding of the energetics of the stratosphere.

With respect to applied climatology, most requests for statistics based on MRN data come from the missile engineer. Means, standard deviations, and extremes of density, temperature, wind, wind shear, and local speed of sound may all have a role in determining the aerodynamic loads to be borne by rapidly moving missiles in their upward trajectory. When the statistics are highly imperfect, structures have to be over-designed as insurance against the accidental destruction of more than a very small percentage of vehicles. As more data are accumulated and statistics become more refined, vehicle structure may be lightened, often permitting a substantial increase in th size of the relatively small payload.

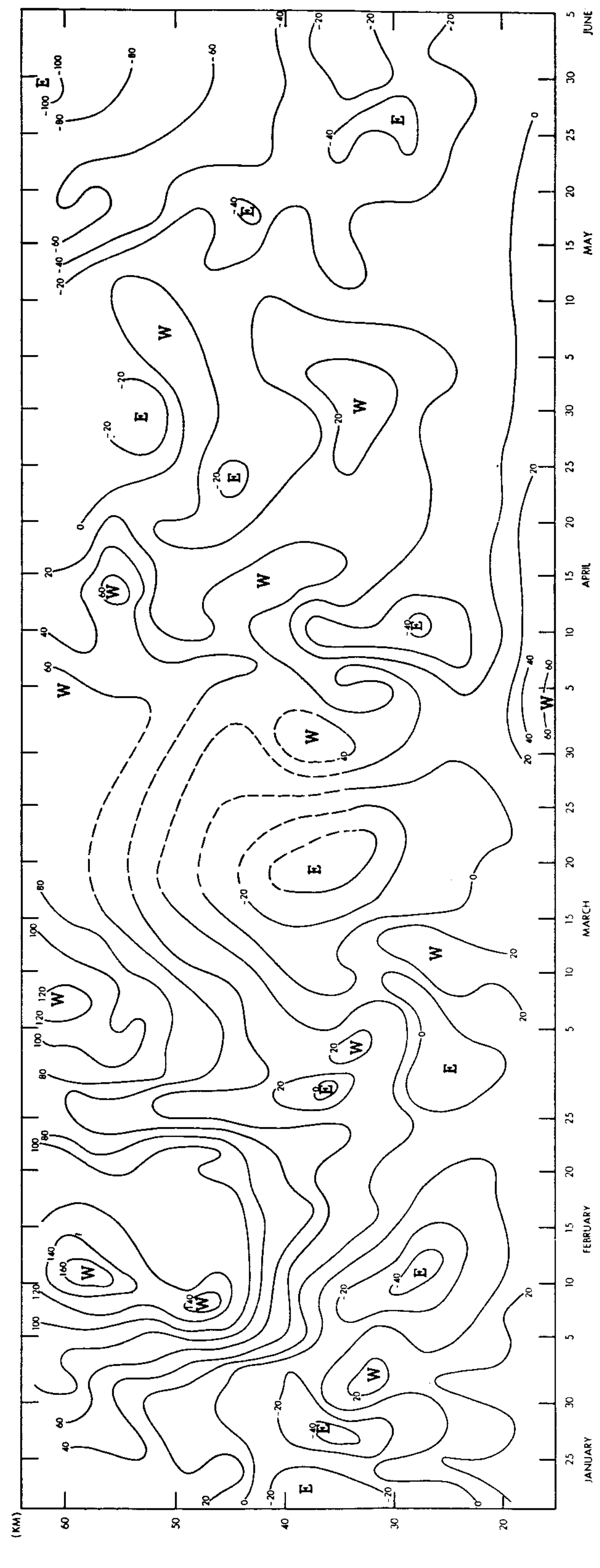


Figure 4.—Zonal wind components, Cape Canaveral, Florida, January 22 to June 5, 1962; west wind positive, in m/sec. Isotachs are dashed through an interval without rocketsonde observations.

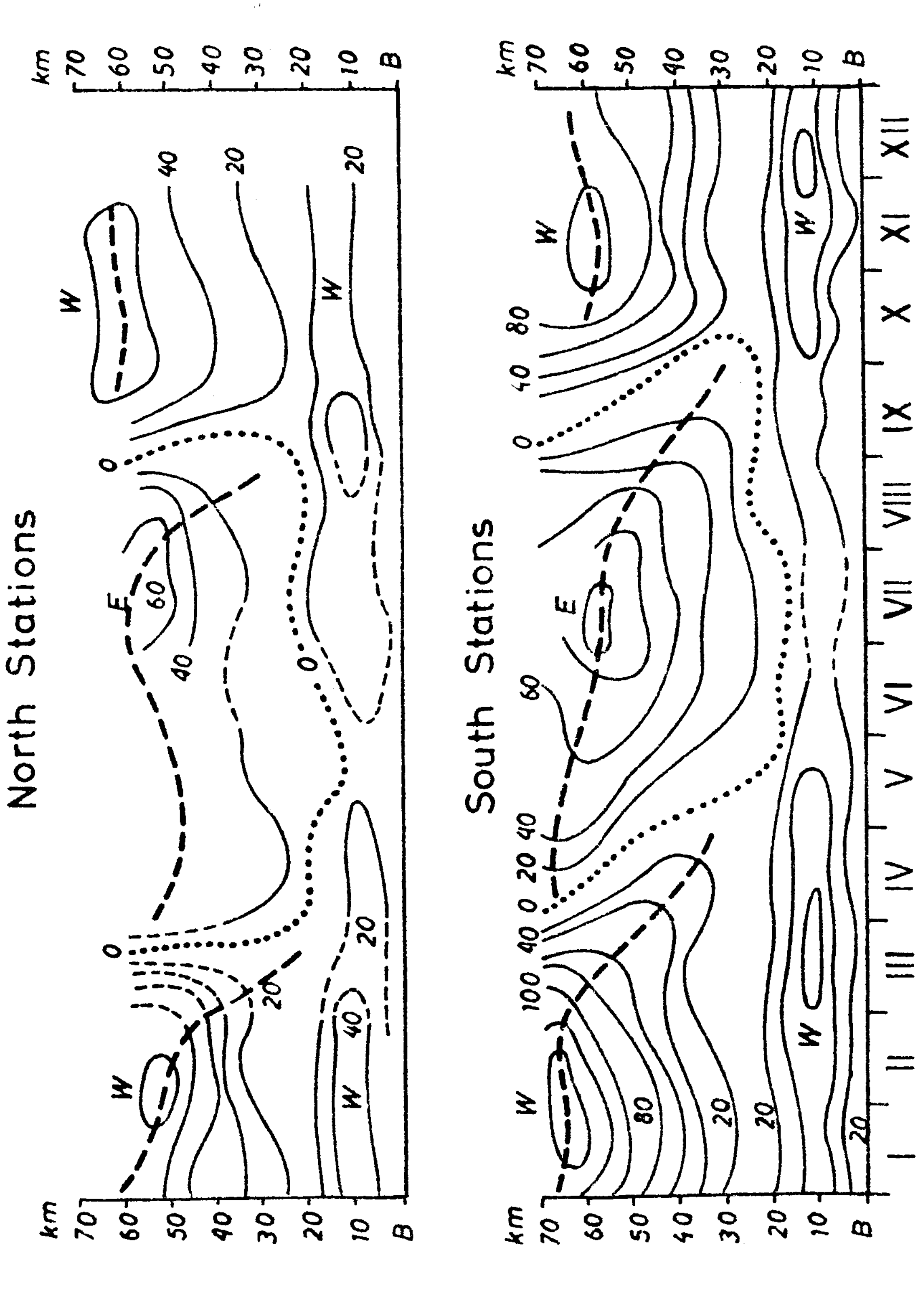


Figure 5.—Annual course of the zonal wind component, based on monthly means for northern MRN stations (~ 60° N) and southern MRN stations (~ 30° N), W for west wind, E for east wind, in kt (ref 4).

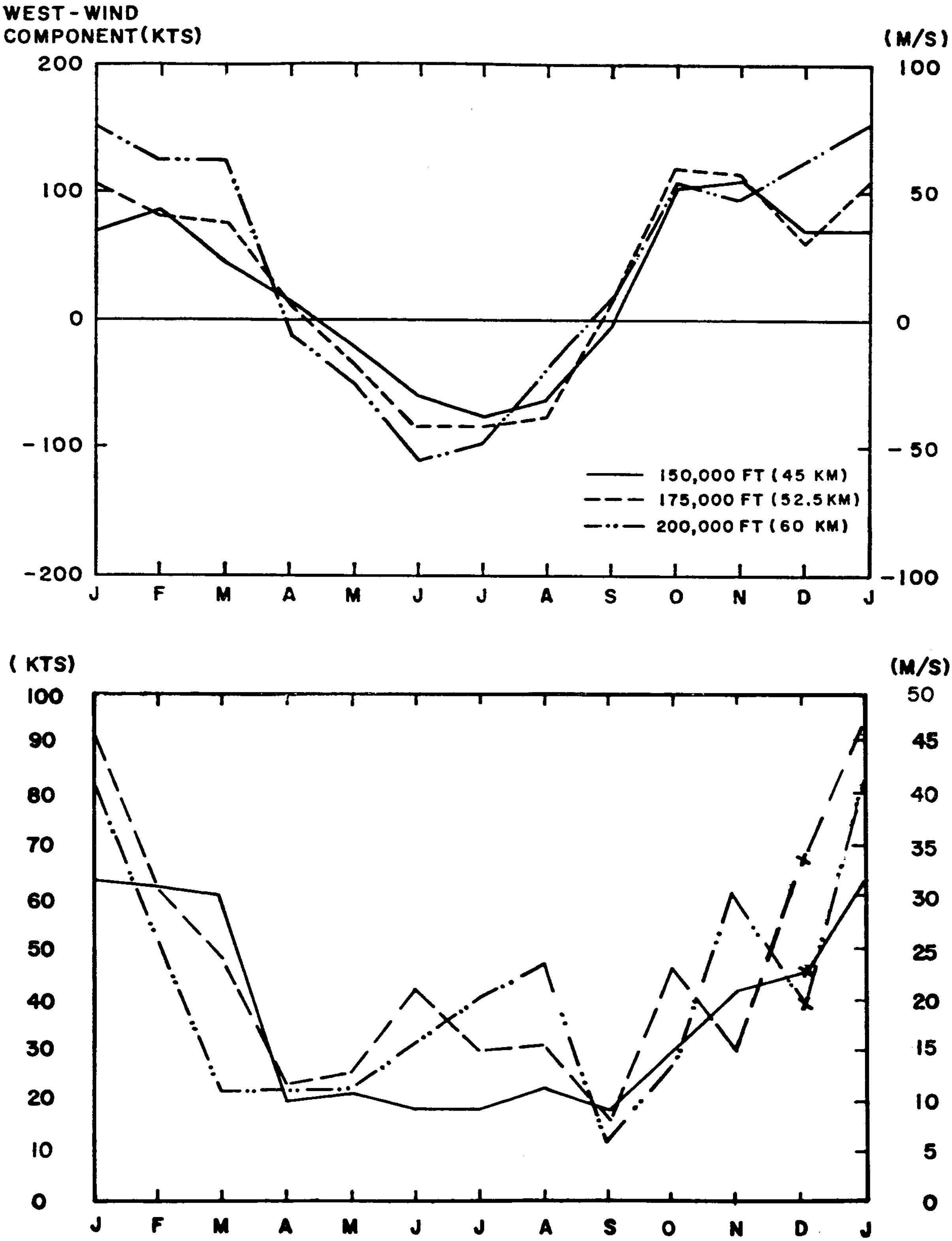


Figure 6.—Annual cycle of the zonal wind component for southern MRN stations (21–38° N). Monthly mean zonal wind component (top); standard deviation of the resultant wind (bottom). Period of record is from October 1959 to August 1961, except December standard deviation is based on 1960 and 1961 data (ref. 5).

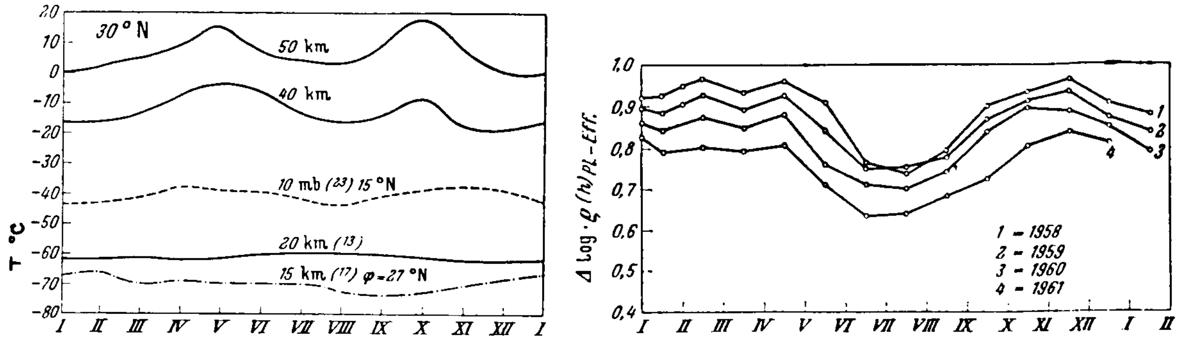


Figure 7.—Semiannual variation in wind speeds in the high atmosphere: left, annual course of temperature by months at 30° N, at 40 km and 50 km compared with that at lower levels at other latitudes at left (ref. 6); right, annual variation of satellite orbital decay during four successive years (ref. 8).

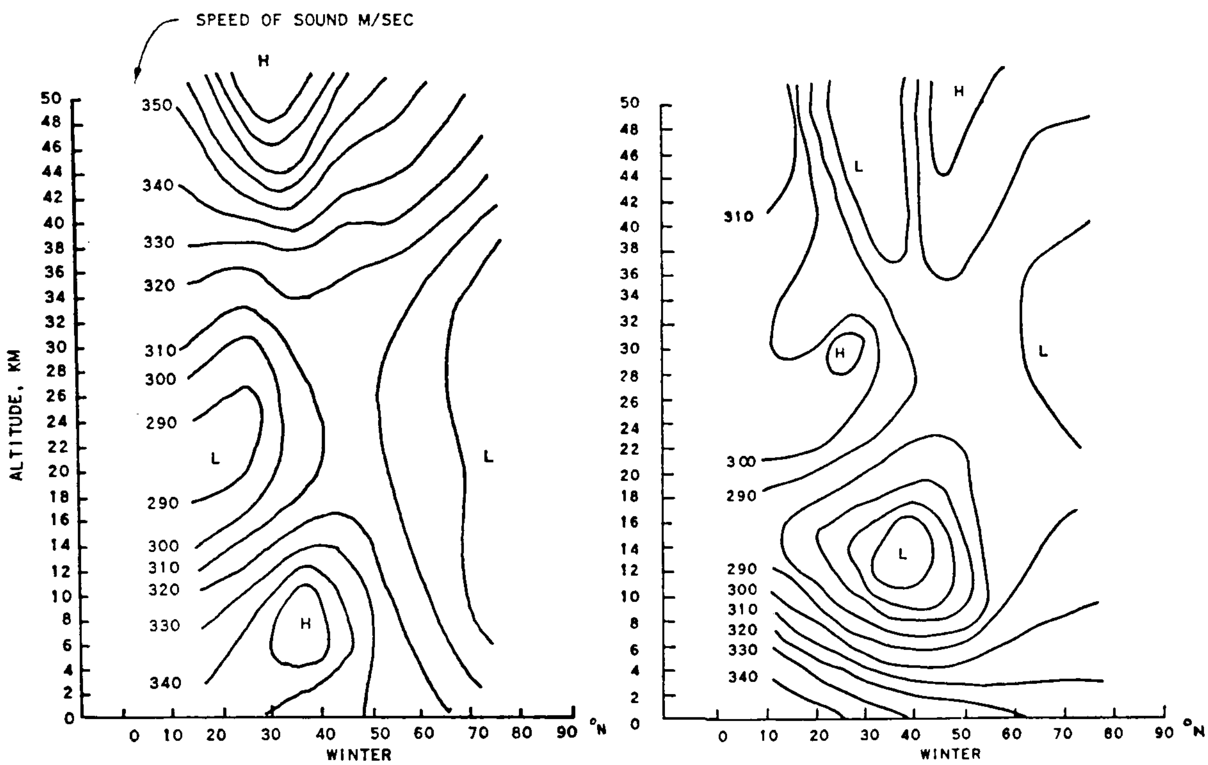


Figure 8.—Sonic structure of the atmosphere as a function of zonal wind and temperature: left, for sound propagating from west to east; right, for sound propagating from east to west.

ANALYSIS OF SYNOPTIC CHARTS FROM MRN DATA

Quite naturally, a synoptic meteorologist is anxious to delineate for the first time the weather systems indigenous to the relatively unexplored layers of the upper stratosphere and lower mesosphere. With so few observations at his command, he must use all of his analytical skills. The customary procedure in such situations is to build up the analysis by hydrostatic principles, working up from one level to the next. A primary advantage of this method is that the analysis based on data at any one level serves as a foundation in building up to the next higher level with its diminished amount of data. Obedience to accepted meteorological principles of analysis, whether they are derived from physical laws or are

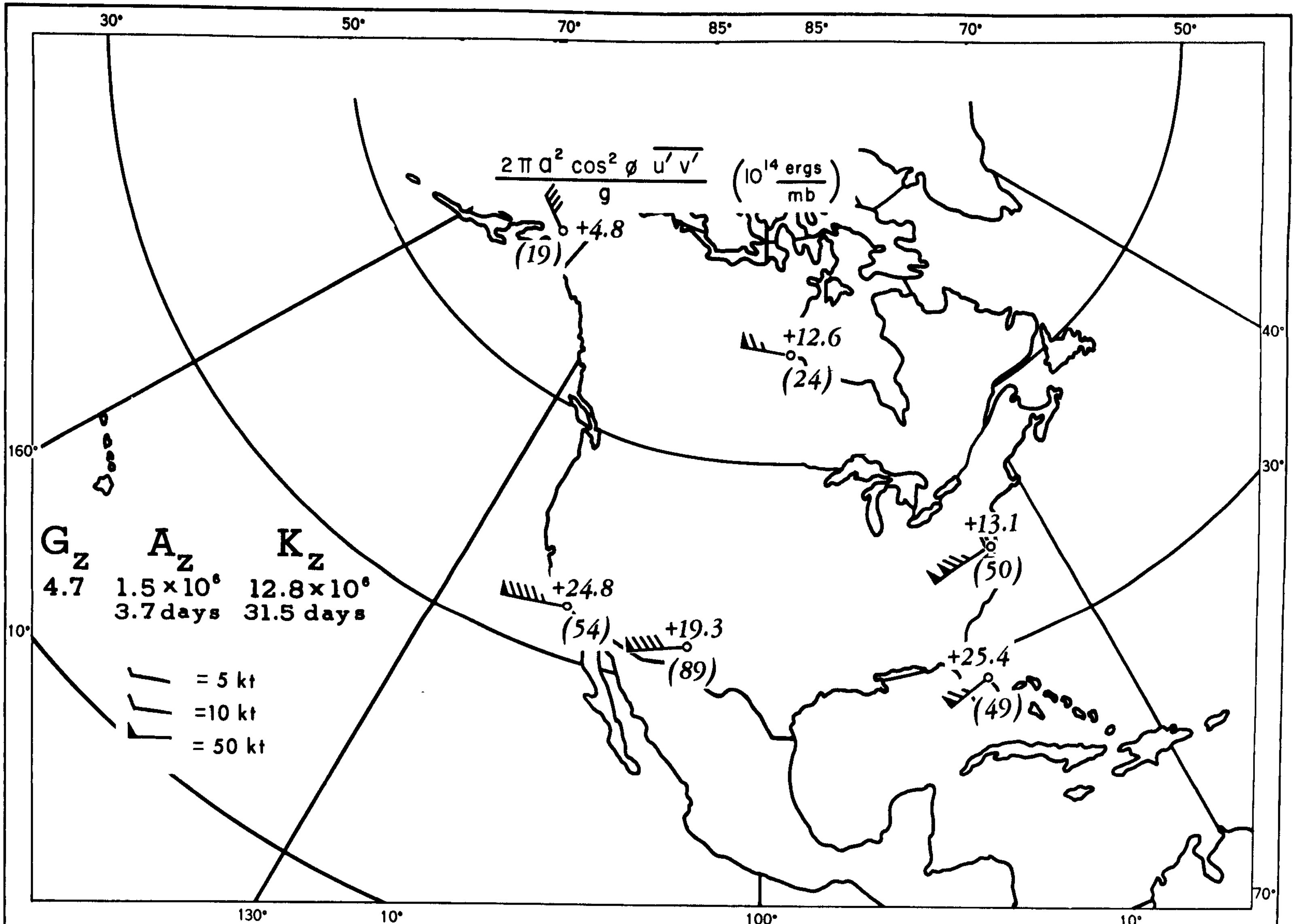


Figure 9.—Meridional transport of relative angular momentum by transient eddies computed at MRN stations (upper number); mean resultant wind and number of observations (lower number, in parentheses) given for MRN stations for the winter months at 160,000-ft level (49 km). In tabular form at the left are the generation of zonal available potential energy G_Z (in ergs/cm^2/sec), the zonal available potential energy A_Z, and the kinetic energy of the zonal flow K_Z (both in units of ergs/cm^2). Below the latter two values are A_Z/G_Z and K_Z/G_Z expressed in days required for generation of the average energy observed during the winter season (ref. 12).

empirical in nature, aids the analyst in the detection of questionable data. Among the meteorologist's empirical tools are the finite number of circulation models that he can reasonably accept for entry in the dataless regions between available reports. Further restrictions limit the amount of change in pattern permissible in going from one level to the next. Techniques for obtaining the most information from the reports of a single station also may be applied by the analyst. Given only a few vertical time sections of winds and temperatures for stations not unreasonably distant from one another, the analyst can apply these single-station techniques to make reliable deductions about conditions within and beyond the network.

By combining several methods of data examination, the analyst attempts to establish a slight redundancy of information as an aid in judging the validity of individual reports. He also is able to make useful estimates of missing values. Then by a cut-and-try method of adjusting circulation and thermal patterns, he finally determines a set of contour charts that best satisfies the available data, violates no meteorological principles, and at the same time obeys the law of parsimony (that the simplest solution according with the known facts should be the most nearly accurate).

One of the synoptic charts presented (fig. 13) includes isotherm patterns. However, because these patterns are exceedingly tedious to establish and temperature reports are still not very plentiful, the remaining charts show contours only. Although a mean temperature for the layer between levels does have to be determined for use in the build-up procedure, this value may be estimated with substantially greater accuracy than the spot temperature at the top of the layer (because the accuracy of temperature measurement tends to decay with height).

The basic steps in the analysis procedure are:

1. Construct a 10-mb (~31-km) chart from rawinsonde data supplemented with rocketsonde data.

2. Compute the height of the 2-mb (~43-km) surface with the aid of temperature time-sections, or lacking these, compute a tentative height by judicious use of supplemental atmospheres.

3. Select rocketsonde winds at the calculated 2-mb height for several days before and after map time.

4. Construct contours in geostrophic agreement with the wind estimated for map time.

5. Determine absolute height of contours to give the best fit to observed winds and computed heights. (If a final height is substantially different from the tentative one calculated in step 2, discard the latter and proceed again beginning at step 3.)

6. Use final 2-mb chart as foundation for the 0.4-mb (~55-km) chart with procedures analogous to step 2–5 above.

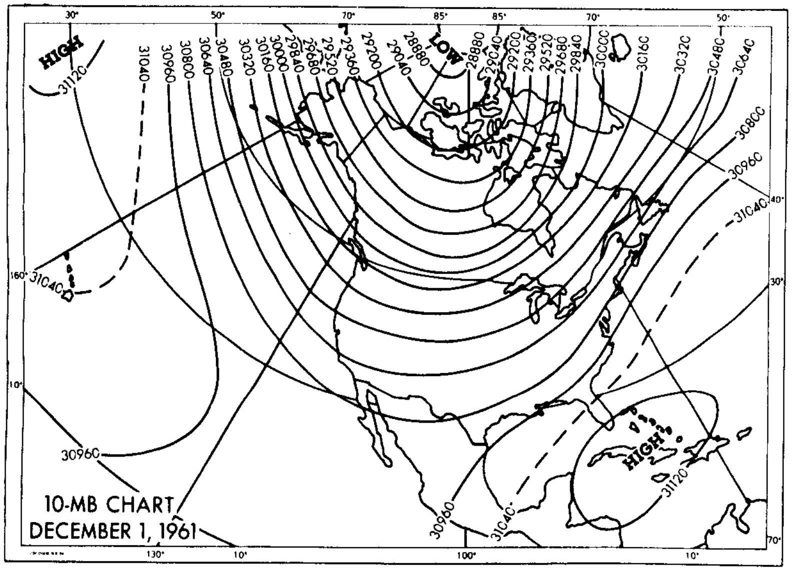
An essential but very tedious part of this process is the scanning and rescanning of reports in order to determine the most probable shape, size, and movement of systems within and beyond the network.

Some examples are presented here from among the many sets of analyses that have been made for dates with relatively complete coverage of reports from the network (ref. 13).

In the set of charts for December 1, 1961 (fig. 10), the polar vortex is shown at a well-developed stage. At 0.4 mb, there were unusually strong west winds that exceeded 280 kt (~520 km/hr) at Wallops Island. At the southern stations, winds at 0.4 mb were still increasing with height while at Ft. Churchill the wind was decreasing with height, indicating relatively warmer air poleward from that station.

For January 20, 1962 (Fig. 11) the pattern shows the initial stages of a radical change, particularly at Wallops Island, where the wind changed to a moderate southerly. At 2 mb, the relatively circumpolar jet stream flow of early December has looped poleward over Alaska and also over the northern Atlantic leaving a trough of massive proportions over western North America.

A time-height cross section of temperatures and winds measured by rocketsonde at Ft. Churchill (fig. 12) shows the intrusion of exceptionally warm air leading to a sharp inversion above 37 km on February 7, 1962. Although there was a residual pocket of cool air in the 25- to 30-km layer, the remainder of the sounding down to the tropopause on that day showed anomolously warm conditions. For several days thereafter, conditions at this station tended toward normal, but another high-level warming was indicated on February 16. An interesting phenomenon is the strong inversion that characterizes these high latitude soundings particularly in cases where the advection of warm air from the north is indicated by vertical wind shear and mean wind. To account for all observed aspects of the phenomenon, a marked subsidence must accompany the development of a polar anticyclone in the upper stratosphere.



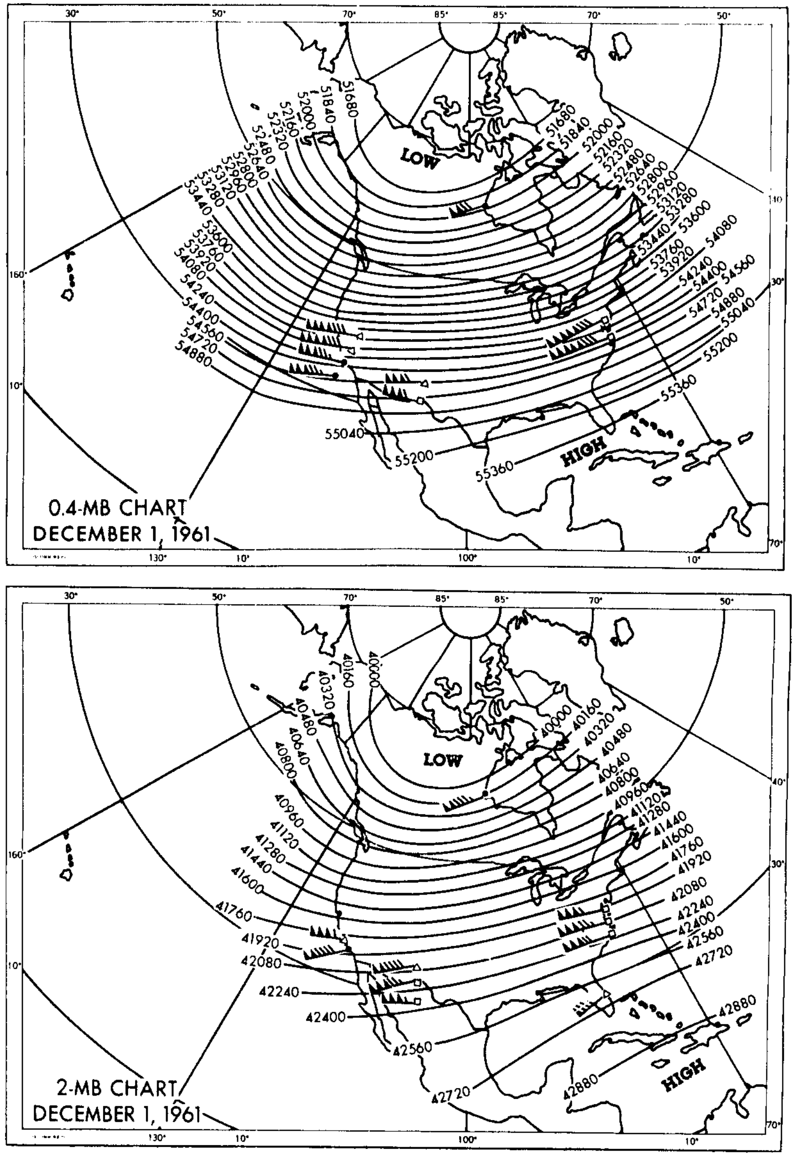


Figure 10.—Synoptic charts at 10, 2, and 0.4 mb for December 1, 1961. The 10-mb analysis is based primarily on rawinsonde data (not shown). Available rocketsonde winds are plotted on the 2- and 0.4-mb charts with a full barb for each 10 kt and a flag for each 50 kt. Triangle at base of wind shaft denotes winds more than one day previous if open, one day previous if filled; filled circle denotes map day; square denotes next day if filled, more than one day later if open. Contour interval is generally 160 m with dashed contours used as necessary for 80-m intervals.

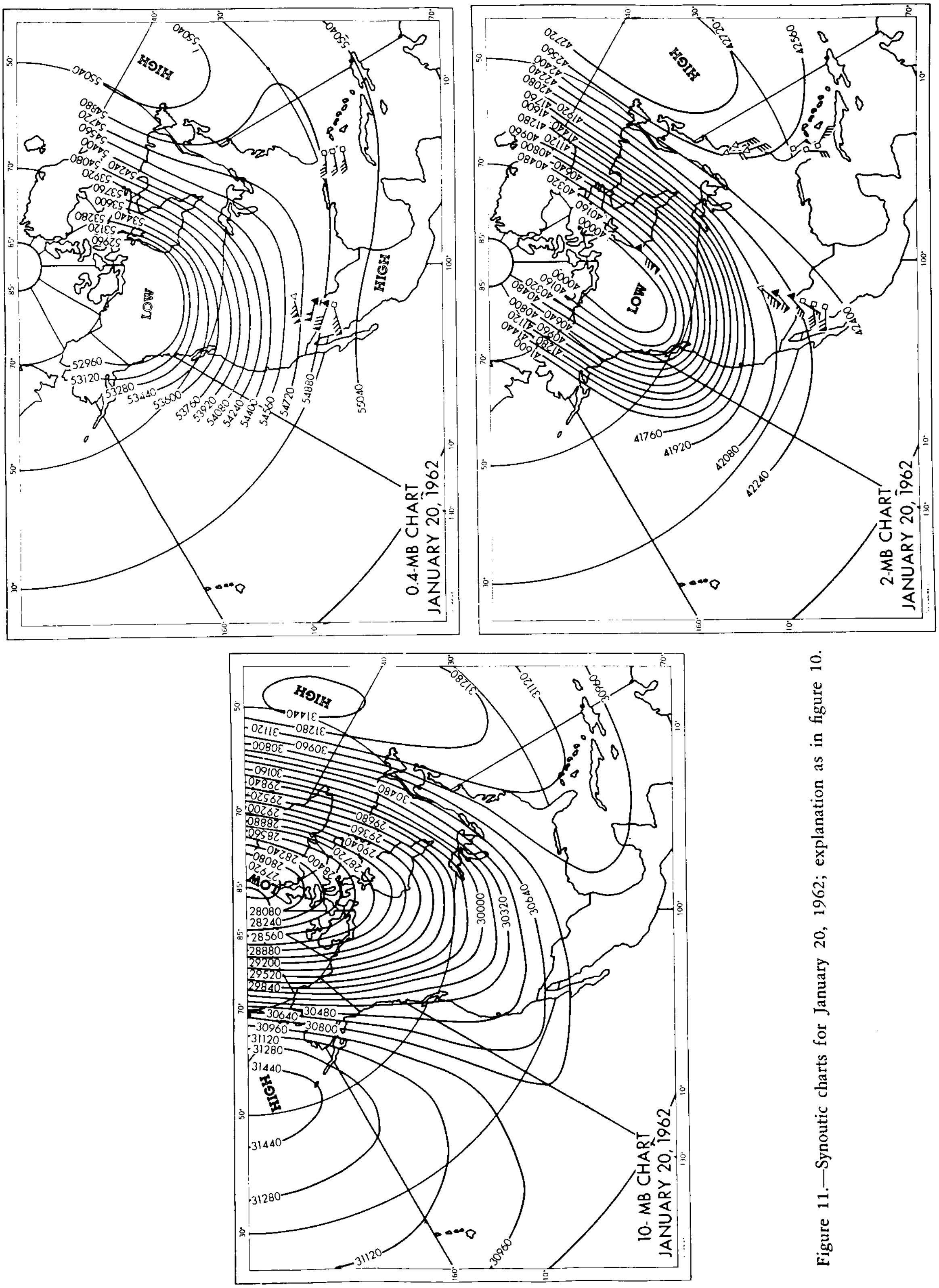


Figure 11.—Synoutic charts for January 20, 1962; explanation as in figure 10.

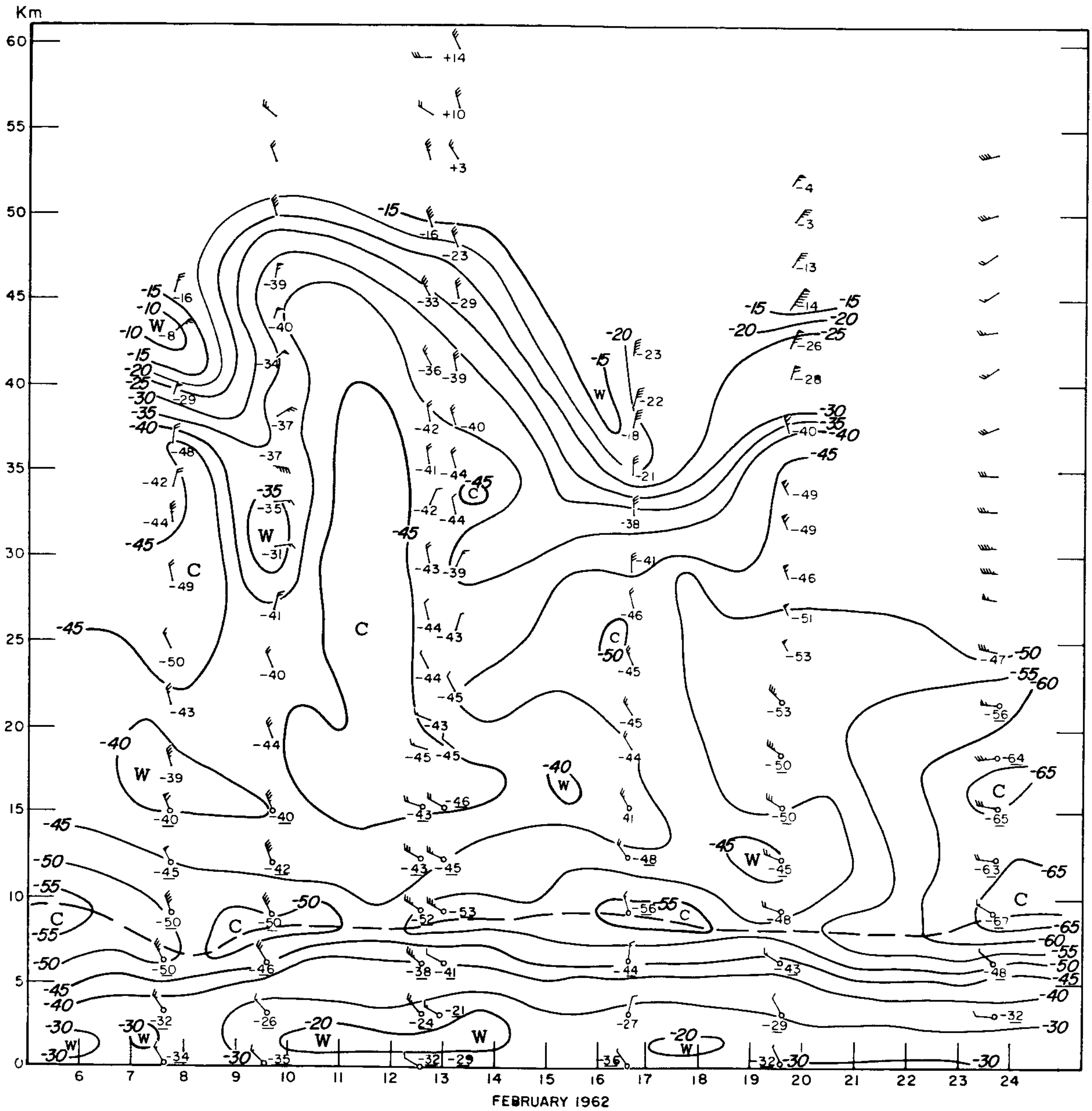
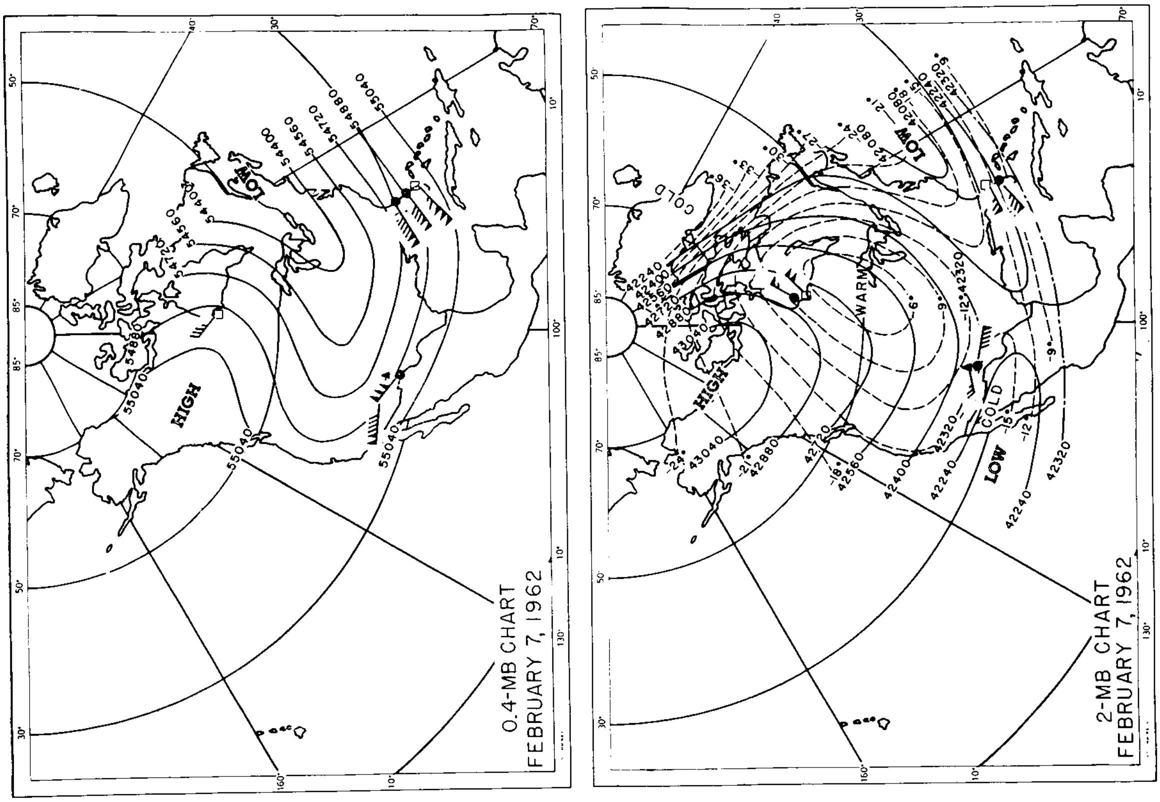


Figure 12.—Time-height cross section of temperatures and winds at Fort Churchill, Manitoba, February 6–24, 1962. Up to about 30 km, analysis is based largely upon radiosonde temperatures (in °C), of which selected values, designated by underline, are included. Other temperatures are from rocketsonde observations. Analysis was terminated near 50 km due to decreasing reliability of reports. Tropopause is shown by dashed line.

The charts for February 7, 1962 (fig. 13) show that a circulation breakdown was in progress. At this advanced stage, the breakdown appears to have been most pronounced near the 2-mb level where a great high pressure area dominated the high latitudes. In the warm air center located over southern Canada, temperatures were about 30° C above the expected values for that region.

Following this major disturbance in the stratospheric circulation, the high-pressure area retreated westward and weakened. By the end of the month, its place over the continent had been taken by the low-pressure trough moving in from the Atlantic. However, when westerly winds were restored over the continent, they did not regain more than a fraction of the strength they had in December. They



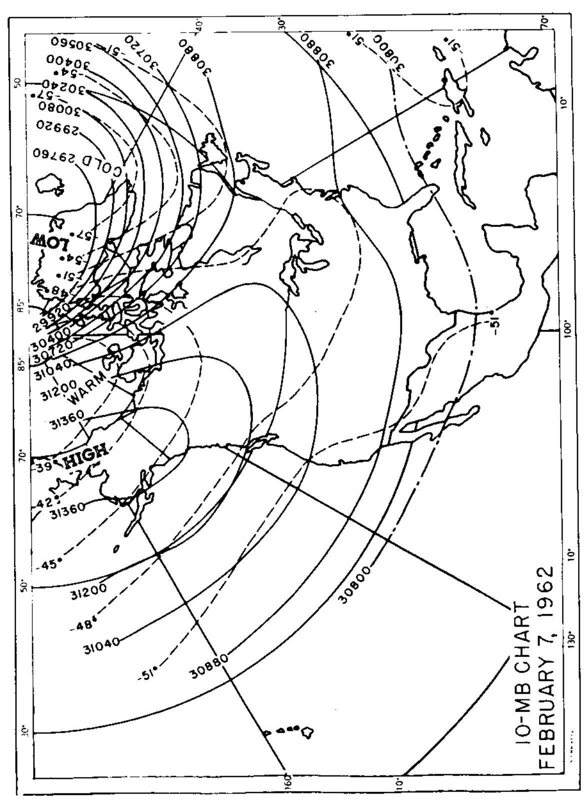


Figure 13.—Synoptic charts for February 7, 1962. Isotherms at 3° C intervals are shown by dashed lines; explanation otherwise as in figure 10 (ref. 14).

weakened rapidly during April and were almost entirely replaced by easterlies by the end of May.

In mid-August, following the usual summertime regime of easterly winds at all stations, a gradual change to westerlies began at high latitudes. By September 26, 1962 (fig. 14), the resurgent westerlies cover the entire continent at 0.4 mb, but have not spread over the southern United States at 2 mb and more evidently not at 10 mb. Unanalyzed MRN data show that, as in previous autumns, the westerlies continued their increase to very high values in December.

The 10-mb charts prepared by the Free University of Berlin (ref. 15, 16) show at least two minor instances of high-latitude anticyclogenesis and stratospheric warming in December 1962. These are followed in early January 1963 by nearly complete restoration of the polar vortex and occurrence of the lowest temperatures of the season. The MRN data for late January permit the analysis of a set of charts for January 27 (fig. 15) when a major stratospheric warming was in full progress. Particularly at 2 mb, the high-latitude circulation was completely reversed. Available radiosonde reports indicated that 10-mb temperatures at points over northern Canada rose by as much as 80° C to values above the freezing point. Although there were few measurements of temperatures by rocketsonde during this period of greatest activity, most of them show unusually warm air somewhere between 30 and 50 km.

How the approach of an event of the sort described here appears to the station observer is illustrated by the time section of wind reports from Point Mugu, California (fig. 16). West winds, that at 35 km exceeded 75 m/sec, were observed on Friday, January 18, 1963. With resumption of observations on Monday, January 21, easterly winds were found above 35 km as a result of the southward expansion of the growing polar anticyclone. Equally abrupt changes were observed over Wallops Island, Virginia, during the same weekend. Obviously, during such periods of rapidly changing conditions, observations with at least daily frequency are required.

There are a number of other interesting features in figure 16. West winds reappeared at the top of the sounding on January 25 and progressed downward until the east winds have been completely excluded on January 31. This feature is frequently found in cases of this type and suggests that normal cooling and shrinking of the atmosphere at high latitudes constitute the mechanism by which the effects of anomalous warmings are gradually eliminated. The degree of restoration of the initial conditions is shown by the generally strong west winds of mid-February.

CONCLUDING REMARKS

Although the results discussed may be very impressive to the uninitiated, a word of caution is appropriate. Due to the very short period of record, most of the statistical results so far published do not represent normal values. The user should certainly endeavor to obtain figures based on the longest record and most recent information.

Briefly, the major findings based on MRN observations can be recapitulated as follows:

The vertical shear of the zonal winds through the 25 to 55-km layer requires a generally decreasing temperature in the horizontal from the summer pole across the equator to the winter pole. In the layers above 55 km, the region of the polar night remains warmer than the sunlit regions to the south through the agency of one or more of the recently proposed mechanisms, such as heating by recombination of atomic oxygen, as suggested by Kellogg (ref. 18), compressional heating by subsidence in polar regions or horizontal heat transport by eddies in the mesopheric circulation.

The semiannual temperature maximum observed in recent years at 30° N near the 45-km level still demands explanation. However, there is a possibility that this phenomenon will not appear in the monthly averages for 1962 and 1963, in view of the powerful mixing forces that characterized the midwinter circulation of those years.

In the layers sounded by the meteorological rocket, diurnal and semi-diurnal changes of both temperature and wind have been shown by recent investigations (ref. 19) to increase with height, becoming an order of magnitude larger than those at high rawinsonde levels. Whenever rockets are available and as sensors become more accurate, better determinations of these changes ought to be obtained by additional special series of observations, launched at different times of the year and over a large range of latitude. Meanwhile, for some purposes, network observations, because they are now taken principally at midday, are not completely representative of the daily mean or indicative of conditions at other times of the day.

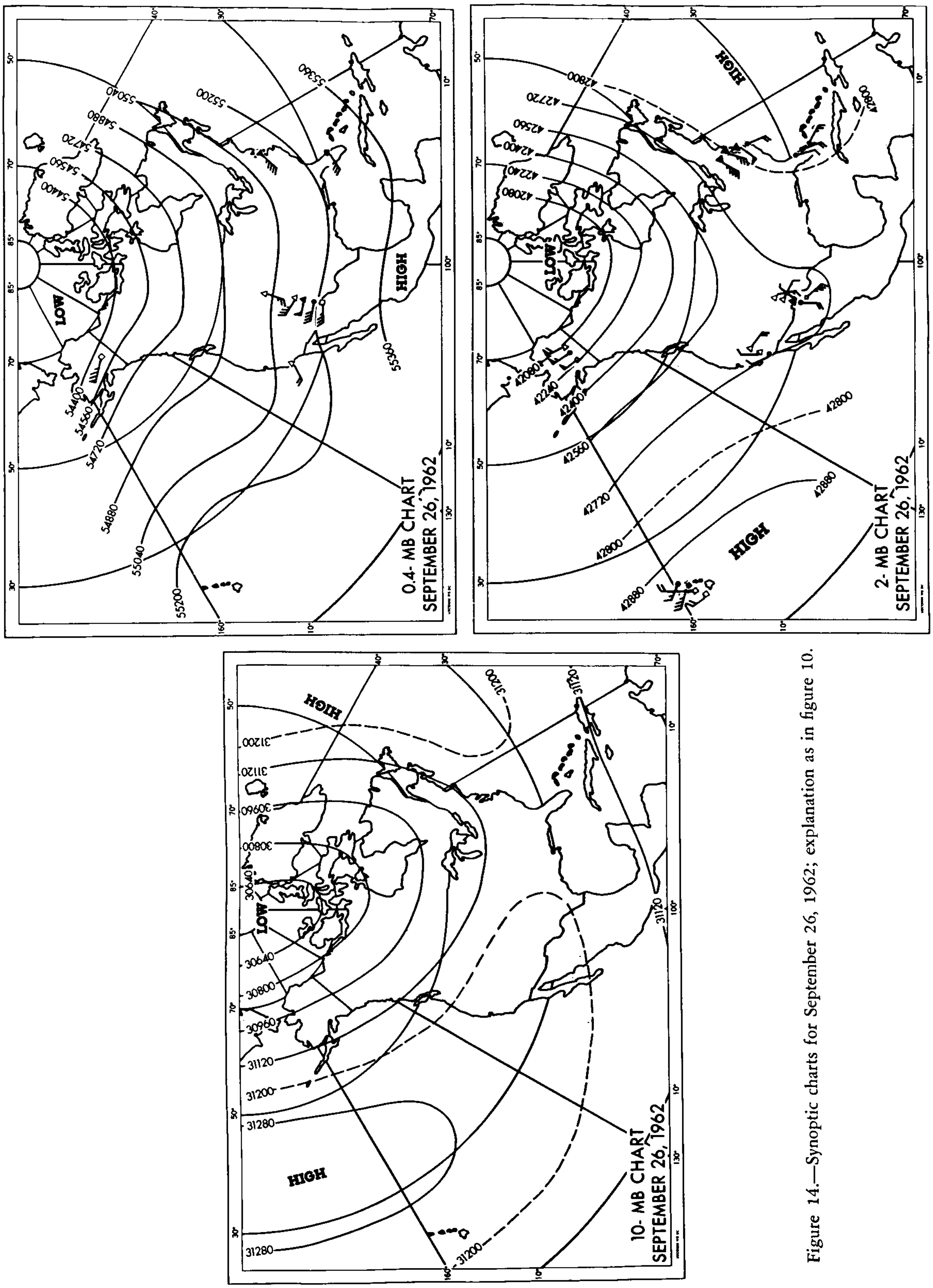


Figure 14.—Synoptic charts for September 26, 1962; explanation as in figure 10.

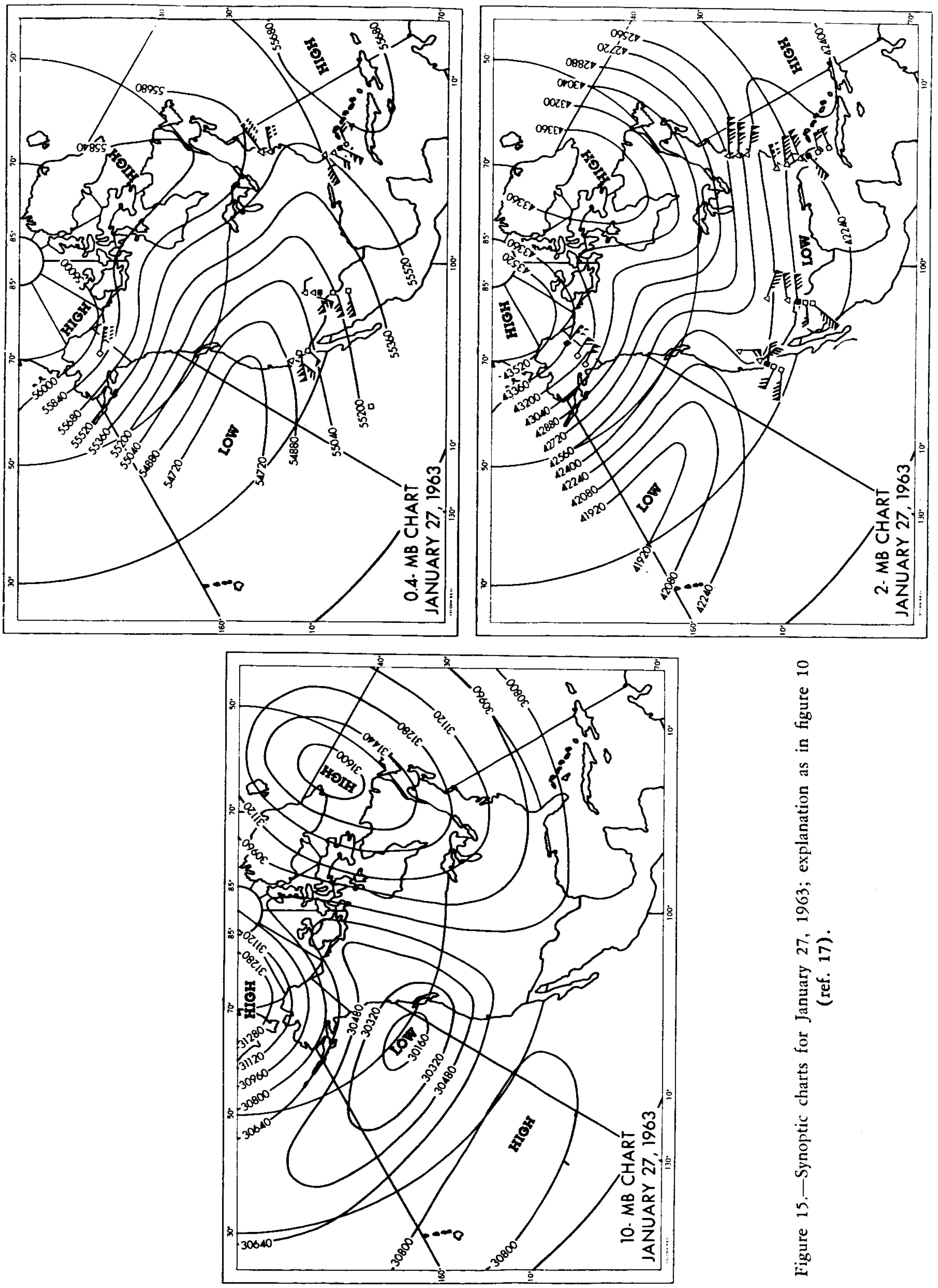


Figure 15.—Synoptic charts for January 27, 1963; explanation as in figure 10 (ref. 17).

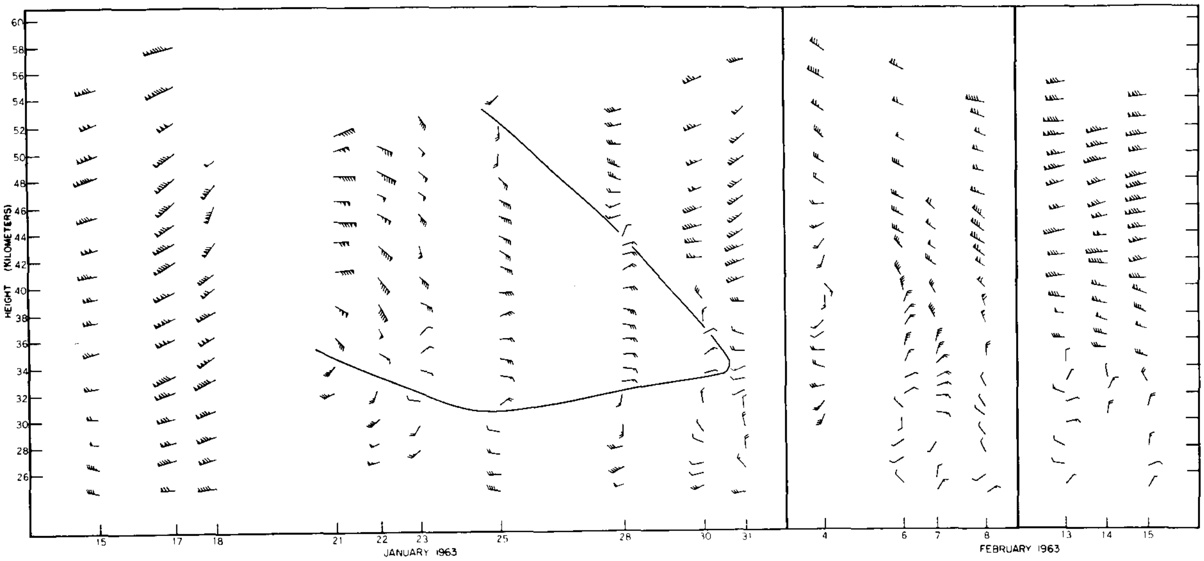


Figure 16.—Time-height cross section of observed rocketsonde winds for Point Mugu, California, January 15 to February 15, 1963. Winds are oriented from the top of the section for north winds and from the left for west winds; full barb for each 10 kt and flag for each 50 kt. Region of each winds in January is marked off by a solid line (ref. 17).

The annual cycle in zonal winds includes a summer period of east winds and a slightly longer winter period of substantially stronger west winds. The autumnal reversal from east to west winds may take place very gradually with the westerly flow appearing first at high latitudes near the present maximum level of MRN soundings and thereafter spreading southward and downward. After the winter westerlies are fully established over network stations, they are sometimes replaced within one or two days over limited areas by easterlies associated with anticyclogenesis at high latitudes. When such interruption by anticyclogenesis takes place before mid-February, the westerlies are generally restored once again. However, in April or May there is a final reversal to the summer easterlies. This spring reversal tends to be more abrupt than that of autumn, taking place in about ten days, sometimes in the form of a merger of polar anticyclogenesis with the northward spreading belt of subtropical easterlies.

Marked changeovers to strong easterlies were revealed by network stations in late January or early February of 1961, 1962, and 1963, but with increasing intensity leading to the huge maximum of 1963. Thus, while the 1961 wind reversal, observed at Wallops Island, scarcely affected the 30-km circulation, the great 1963 reversal dominated the hemisphere and extended downward to upset the circulation in the low layers of the stratosphere. This year-to-year variation in the amount of cellular activity indicates that the degree of horizontal mixing, and thus, for example, the resulting meridional exchange of tracers like ozone and radionuclides may vary markedly from one winter to the next.

The recent extension of the synoptic stratosphere to 55 or 60 km has revealed other interesting features of the transient systems that move through the upper stratosphere and lower mesosphere. On summer maps, the relatively slight perturbations superimposed upon the circumpolar easterly flow are almost undetectable. During the changeover seasons, the winds themselves are weak but show a relatively large percentage variability. In winter, a large absolute variability is superimposed upon even larger mean winds. In late January, this variability is particularly large due to the tendency for a middle-latitude wind reversal with maximum intensity near 45 km.

There is increasing evidence that 45 km is the source level of the circulation breakdown and sudden heating that has been observed at and below the 10-mb level in several of the winters since 1952. Interestingly, this layer of maximum activity coincides with the portion of the ozone layer heated most strongly by solar radiation. The development of strong perturbations at this level is necessary to an intense horizontal heat transport from low to high latitudes. The manner in which this phenomenon of the high stratosphere also is able to influence the circulation of the lower stratospheric levels appears to be an important link in the process by which both heat and ozone are carried down to the lower stratosphere and then concentrated at high latitudes in the colder months of the year.

Mounting evidence points to close similarity between the vertical motions and horizontal transports, associated with the respective jet streams of the tropopause and stratopause levels. Extension of this similarity suggests that the same counter-gradient heat flux found in the layers just above the tropopause-level jet will be found just above its counterpart at the stratopause. The existence of such a counter-gradient heat flux in the mesosphere might explain the warmth of the wintertime pole in the layers above 55 km, partially or entirely without recourse to heating by subsidence and recombination in the layers of atomic oxygen.

In conclusion, it must be agreed that these are exciting and worthwhile results coming from a modest network that has operated for only a short period with equipment of which much is still in the development stage. The improvements being made in every stage of the observational process are already providing data that will lead to many additional important discoveries.

Permission granted by Professor Richard Scherhag for the use of 10-mb charts analyzed at the Free University of Berlin is gratefully acknowledged. Analysis of the 2-mb and 0.4-mb charts was performed jointly by Frederick G. Finger and the author. Processing and graphing of data were performed by members of the U.S. Weather Bureau Stratospheric Meteorology Research Project, which is jointly sponsored by NASA, AEC, NSF and the U.S. Navy.

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ROCKET SOUNDINGS IN THE MESOSPHERE

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CONTENTS

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William Nordberg

PHYSICS OF THE MESOSPHERE

The feature of a steadily declining temperature with altitude has been recognized as a distinct characteristic of the atmospheric region between 50 and 90 km long before the onset of systematic exploration of the upper atmosphere by means of sounding rockets. It was then proposed that this region be named *mesosphere*.

The mesosphere is bounded by the *stratosphere* at the bottom and by the *thermosphere* at the top, both regions of generally positive temperature gradients with altitude. During recent years a variety of rocket-borne experiments have contributed to bringing the numerous characteristics of these regions into clearer focus. It has been learned that there are consistent exceptions to the steadily declining temperature-altitude profile in the mesosphere (ref. 1) and that persistent, large scale circulation systems which characterize the dynamics of the lower mesosphere change their behavior rather abruptly at the higher altitudes (ref. 2). These features are perhaps of equal or even greater significance than the existence of a temperature-lapse rate. The eventual goal of the rocket experiments in the mesosphere is to explore these characteristics to the extent that the physical processes which determine the state of this region can be fully understood. Characteristics such as temperature profiles, wind fields, and compositional structure are simply manifestations of the underlying physical processes.

The thermal structure of the mesosphere is thought to be determined mainly by the absorption of solar ultraviolet radiation by ozone and by the loss of energy through the emission of infrared radiation by ozone and carbon dioxide. Heating rates ranging from about 15° C per day near the summer pole at the mesosphere to no heating near the winter pole at the top of the mesosphere have been computed (ref. 3). Computed cooling rates due to the emission of infrared radiation by carbon dioxide and ozone are of comparable magnitude, but the distribution of these energy sinks with latitude and season is substantially different from the distribution of the heating sources (ref. 3). The global variation of this radiative energy balance profoundly affects the wind patterns which in turn relate to the convective exchange of energy.

On the basis of these physical processes the mesosphere is unique in many respects. It is the highest region of the atmosphere where the existence of circulation systems in the meteorological sense have been observed; systems which change periodically with season and are primarly driven by latitudinal temperature gradients (ref. 2). At higher altitudes, above 70-90 km, the nature of the circulation changes abruptly probably due to the predominance of oscillatory forces such as tides and possibly due to interaction of the medium with electric and magnetic fields. Wind fields above 80 km have not exhibited any seasonal regularities. This boundary at 80 km also coincides roughly with the level where diffusive separation between the heavier and lighter constituents of the atmosphere begins to overcome the mixing processes which dominate below 80 km and which are responsible for keeping the gross composition of the atmosphere nearly constant from the ground up to about 80 km. Despite this constancy of gross molecular weight, the thermal structure of the mesosphere is highly sensitive to minor variations in the concentration of photochemically active constituents such as atomic oxygen and ozone which take place in this region. Up to the 80-km level these constituents have no effect on the gross molecular weight. Above 80 km dissociation of molecular oxygen in addition to gravitational separation between lighter and heavier gases contributes to a rapid decrease in molecular weight.

The interactions between short term variations in solar radiation and the state of the atmosphere in the 50- to 90-km region are also of profound interest. At higher altitudes (200-300 km) such direct interactions have been positively identified, (ref. 4) while in the stratosphere and troposphere they are not known to exist nor are they likely to occur. It is more likely that certain concurrent features may be found in circulation from the troposphere through the stratosphere well into the mesosphere. If, on the other hand, there is also a direct influence of fluctuations in the shortwave solar radiation on the structure of the mesosphere a link between such fluctuations and "weather" in the lower regions of the atmosphere may very well have been established.

Most of the rocket experiments conducted to date have been either too sparse or not adequately instrumented to permit a fundamental exploration of the physics of the mesosphere. This region is inaccessible to sounding balloons and indirect, ground-based, or satellite measurements have not been very successful yet in obtaining satisfactory measurements of the mesosphere. Therefore, the sounding rocket remains the only useful tool.

The fundamental physics of this region must then be derived from the results of a large number of rocket soundings which should take place at various key locations in the world and which should be conducted within the framework of a globally coordinated program. These soundings should consist of measurements of the typical structure parameters: temperature, pressure, density, wind, and composition. Such measurements are well within the capability of existing instrumental techniques except perhaps for the measurement of composition. Measurements of the trace constituent composition in the mesosphere, though very important, has been grossly neglected during past years.

Finally, with the advent of large spacecraft and manned spaceflight, the exploration of the mesosphere has taken on a new aspect. In many instances, launch vehicles as well as re-entering spacecraft are expected to pass through critical phases of their flight in the 50- to 90-km region. In order to design appropriately for these conditions, engineers are keenly interested in obtaining the best possible knowledge of the anticipated flight environment. Density and winds are the parameters of greatest importance for these purposes. This practical application, plus the fact that the basic physical processes which take place within the mesosphere still pose many most challenging questions, clearly spell out the necessity for further experimental exploration.

EXPERIMENTAL TECHNIQUES

Launch Vehicles

Rocket vehicles used for upper atmosphere exploration can be generally classified into three categories. This classification applies to the aspect of cost, size, and complexity, as well as to the capability of the rocket to carry a given weight to a given altitude. For the purposes of this discussion the three categories shall be defined as: small, medium and large.

Small rockets generally carry payloads of about 1-5 kg and small diameters (less than 12 cm) to altitudes of 50-70 km. They are relatively inexpensive with the rocket and payload costing approximately $2,000. The entire launch operation can be performed with a minimum of complexity, generally requiring only a simple, easily transportable launching tube and crew of less than five. Simple sensors carried by these rockets perform temperature and wind measurements in the stratosphere and wind measurements in the lower mesosphere. The rockets can be launched frequently and in fairly large numbers. This has made them useful as launch vehicles in synoptic soundings as part of the United States Meteorological Rocket Network (ref. 5). In the United States the Loki II, also called HASP, and the ARCAS, are typical of such vehicles. These rockets and their associated instruments have been described in connection with the Meterological Rocket Network (ref. 5), MRN.

Large sounding rockets carry payloads of up to 100 kg and large diameters (30-40 cm) well into the thermosphere (200-300 km). They are relatively expensive (>$25,000) and require fairly complex launch installations with crews of more than ten. A typical example of a United States rocket of this category is the Aerobee (ref. 6). Because of the expense and complexity it is not practical to use such rockets in synoptic programs.

Rocket vehicles of *medium* category are the best suited for experiments in the mesosphere. They posess sufficient thrust to carry payloads of 30-40 kg and 15-20 cm diameters to altitudes of 100-200 km. The cost (about $10,000-25,000 including payload) is such that "semi-synoptic" programs at several sites with launchings at periodic intervals—though not continuous—are permissible. A crew of less than 10 can usually handle the launch operation from a rail launcher. In the United States, two stage rockets, using the Nike booster as a first stage, are most common. The Cajun rocket (ref. 7), which has been most commonly used as a second stage since the International Geophysical Year (IGY) has now been succeeded by the more powerful Apache (ref. 8). A typical Nike-Cajun rocket configuration is shown in figure 1.

Radar Tracking of Chaff

The only experiment which has been successfully performed in the mesosphere by using small rocket vehicles is the measurement of wind by means of dispersing chaff (ref. 9), whereby the drift of the chaff with the wind is tracked by radar on the ground as the chaff descends from altitudes of 80 km or below. In the upper part of the mesosphere, however, it is very difficult to measure wind by methods of dispersing solid materials such as chaff because the fall velocity of the chaff approaches free fall very rapidly with increasing altitude (ref. 9). Another disadvantage of the chaff method is the fact that the chaff, ejected from the rocket near apogee disperses rather rapidly (in many cases within about 20 km), as it falls through the atmosphere.

Sodium Vapor Ejection

Efforts have been made very early in the history of rocket soundings to measure winds by means of ejecting and tracking aerosol-type particles or vapors from rockets. These payloads usually consist of smoke generators or vaporizors and require therefore, rockets of the medium category. The most successful of these techniques has been the method of injecting sodium vapor into the atmosphere between 70-200 km during twilight conditions. Interaction of sunlight with the sodium vapor (resonance radiation) causes the sodium trails to be luminous, and with the proper ejection technique the sodium remains visible for periods up to 30 min at middle latitudes.

The trail moves instantly with the atmospheric wind field, and its track is recorded by an array of cinetheodolite cameras which are spread over the ground on very long baselines (>50 km). The drift motion is determined by triangulation of significant features such as a sharp kink in the trail (figure 2). This method was originated by Manring (ref. 10) and an estimated order of 50-100 soundings have been carried out at many locations of the globe. Figure 2 also shows how two different techniques, namely the

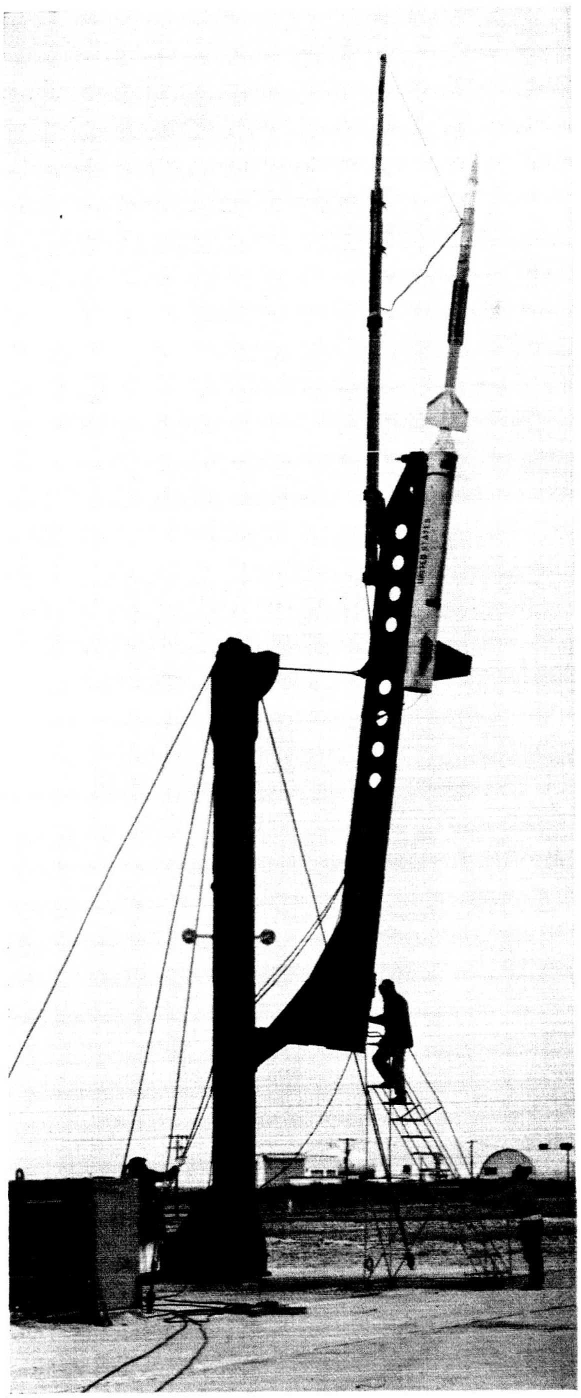

Figure 1.—Nike-Cajun rocket with grenade experiment ready for launch at Wallops Island.

sodium release and acoustic grenade techniques, were combined in one experiment. Flashes from the grenades can be seen in the center of figure 2.

A disadvantage of the sodium technique is that it can be carried out during only a few minutes every 12 hours, during a time when the region above 70 km is illuminated by the sun, in order to produce the glow in the trail and when the cameras on the ground are in darkness, in order to permit proper exposure of the film. Also, the experiment must be carried out in clear skies.

Figure 2.—Photograph of sodium trail exposed with simultaneous grenade experiment. Flashes from grenade explosions can be seen near center of photograph. Distinct features such as sharp bends in the trail which indicate extreme wind shears are used as identifying reference when triangulating the trail from various camera sites.

Although this experiment functions only in the upper mesosphere—the resonance glow cannot be induced below 60-70 km because of the absorption of the incident sunlight by natural sodium in the atmosphere—it has produced valuable information on the tremendous wind shears in the transition region between the mesophere and thermosphere. The great advantage of this technique is that the continuous trail enables the observation of the fine structure of the wind with great detail. Research is progressing at this time on self-luminous vapors which glow for a sufficient time and with sufficient intensity to permit this type of wind measurement throughout the night.

Acoustic Grenades

The direct measurement of temperature which can be performed in the stratosphere by means of extremely small resistance thermometers (ref. 5) (thermistors) becomes questionable at altitudes above 50 km (ref. 11). In the mesosphere, therefore, temperature must be measured by more complex, indirect methods. The method most commonly used in the rocket-grenade technique.

In this experiment, grenades are ejected and exploded at altitudes up to 90 km at regular intervals during the ascent of the rocket. They are cylindrical in shape and are ejected forward through the nosecone of the rocket (fig. 3) and contain high explosive, mainly TNT, which is detonated mechanically by means of a lanyard tied to the rocket. The explosives weigh between one and two pounds. Average temperatures and winds in the medium between two grenade explosions are determined by measuring exactly the time of explosion of each grenade, the time of arrival of each sound wave at various ground-based microphones, and the exact position of each grenade explosion. Thus, the speed of sound in the layer between two explosions is measured and temperatures can be derived since the temperature is proportional to the square of the speed of sound. Molecular weight is contained in the proportionality factor. Wind speed and direction can be derived from the horizontal drift of the second in the layer.

The grenade experiment requires a highly accurate tracking system. A network of ballistic cameras, or Doppler tracking stations, or a high precision radar of the FPS–16 type is used to determine the co-

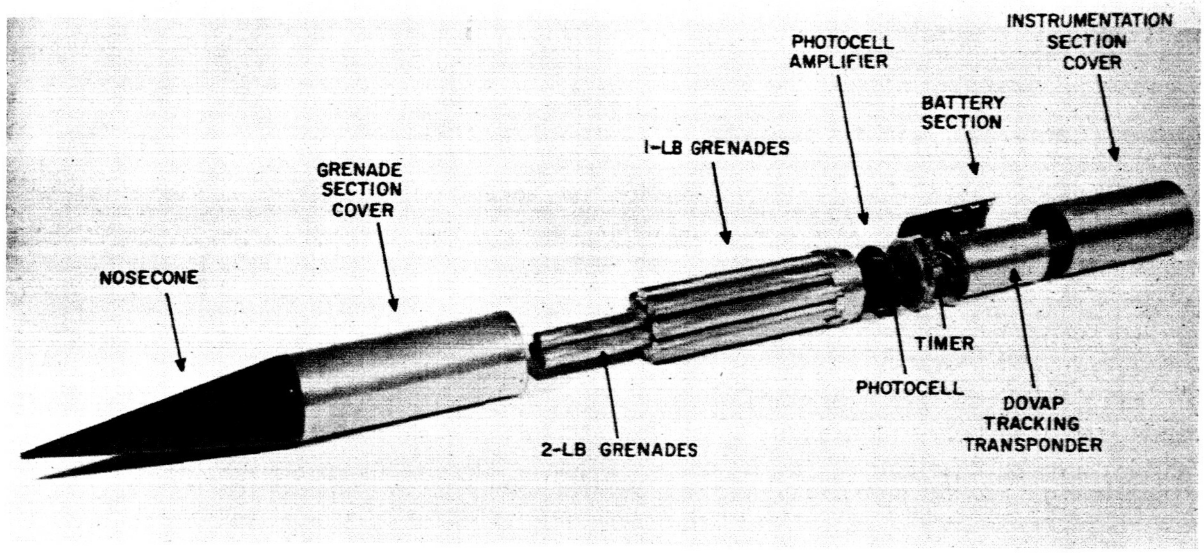

Figure 3.—Grenade experiment payload, exploded view.

ordinates of explosions. A schematic diagram of the essential components of the grenade experiment is shown in figure 4. The highest altitude from which sound returns can be received with present explosive charges and existing sound ranging techniques is about 90 km. The greatest advantage of this experiment is that temperatures and winds can be measured simultaneously which is of great importance in describing the dynamics of the atmosphere, and that the resulting measurements are very accurate. The drawbacks are that only average temperatures and winds in the layer between two grenades can be measured and that a fairly elaborate system of ground instruments for tracking and sound ranging is required. A detailed description of this experiment which has been successfully performed more than fifty times during the past decade is given in (ref. 12).

Falling Sphere

In the altitude region concerned, pressure and density are more susceptible to measurement by *in situ* techniques than temperature. The simplest method in concept is the measurement of density by means of the falling sphere technique. This technique has been originally developed at the University of Michigan (ref. 13), and a large number of successful flights have been carried out since 1952.

In the sphere experiment the drag force (D) exerted on a perfect sphere dropped from a rocket at

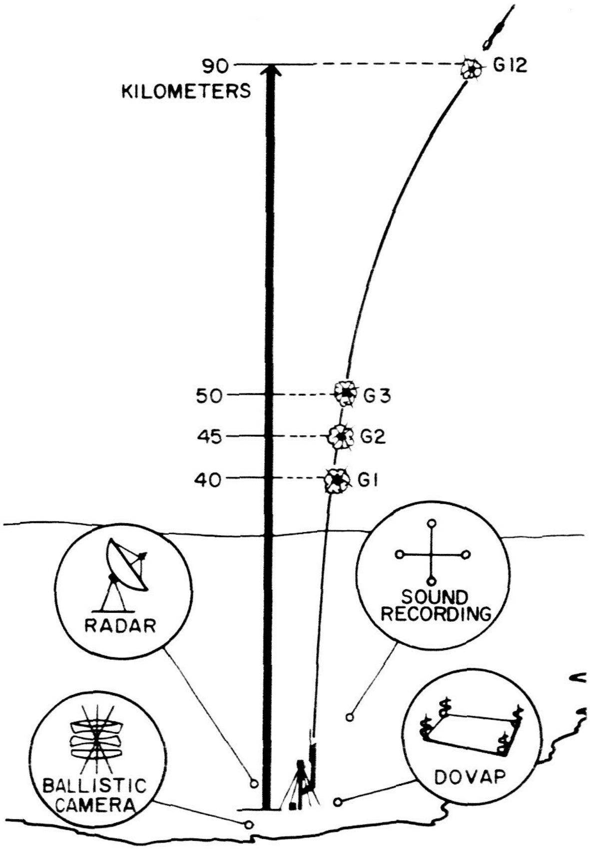

Figure 4.—Schematic diagram of grenade experiment system; radar, ballistic camera, and Dovap tracking systems are indicated. Each individual system or a combination thereof suffices for the experiment. Sound recording site is preferably located directly under trajectory of rocket. G-1 through G-12 indicate altitudes of grenade explosions.

high altitude is measured and ambient density (ρ) is derived by means of the relationship:

$$mg + D = m\ddot{h} = \tfrac{1}{2}\,\rho\,\dot{h}^2\,C_D A + mg \qquad (1)$$

where h is the altitude of the sphere; A, the cross sectional area; and C_D the aerodynamic drag coefficient which is a function of Mach number and must be determined empirically; m, the mass of the sphere, $\dot{h}$, indicates the time derivative of h; and g is the acceleration of gravity which depends on h.

Falling spheres have been used in many different combinations: as rigid shells (as shown in fig. 5) or as inflatable balloons; with built-in accelerometers (active sphere), to measure $\ddot{h}$ directly (fig. 5), or with high precision radar tracking (passive sphere) to determine the drag acceleration from the second derivative of the altitude vs time function given by radar track. Differentiation of the tracking data or integration of the measured accelerations, in case of the active sphere, leads to the velocity, $\dot{h}$, required to solve equation (1) for ρ.

The spheres are usually ejected from the rocket at an altitude of about 60 km and travel along a ballistic trajectory up to about 140 km. Acceleration is determined both along the upward and downward leg of the trajectory. Winds can be measured with inflatable spheres at altitudes below 50 km from the horizontal drift determined by radar. Density measurements with large (1-2 meters) passive inflatable spheres have been obtained up to 110 km (ref. 14). Results from smaller, rigid, active spheres have been reported by Jones (ref. 15).

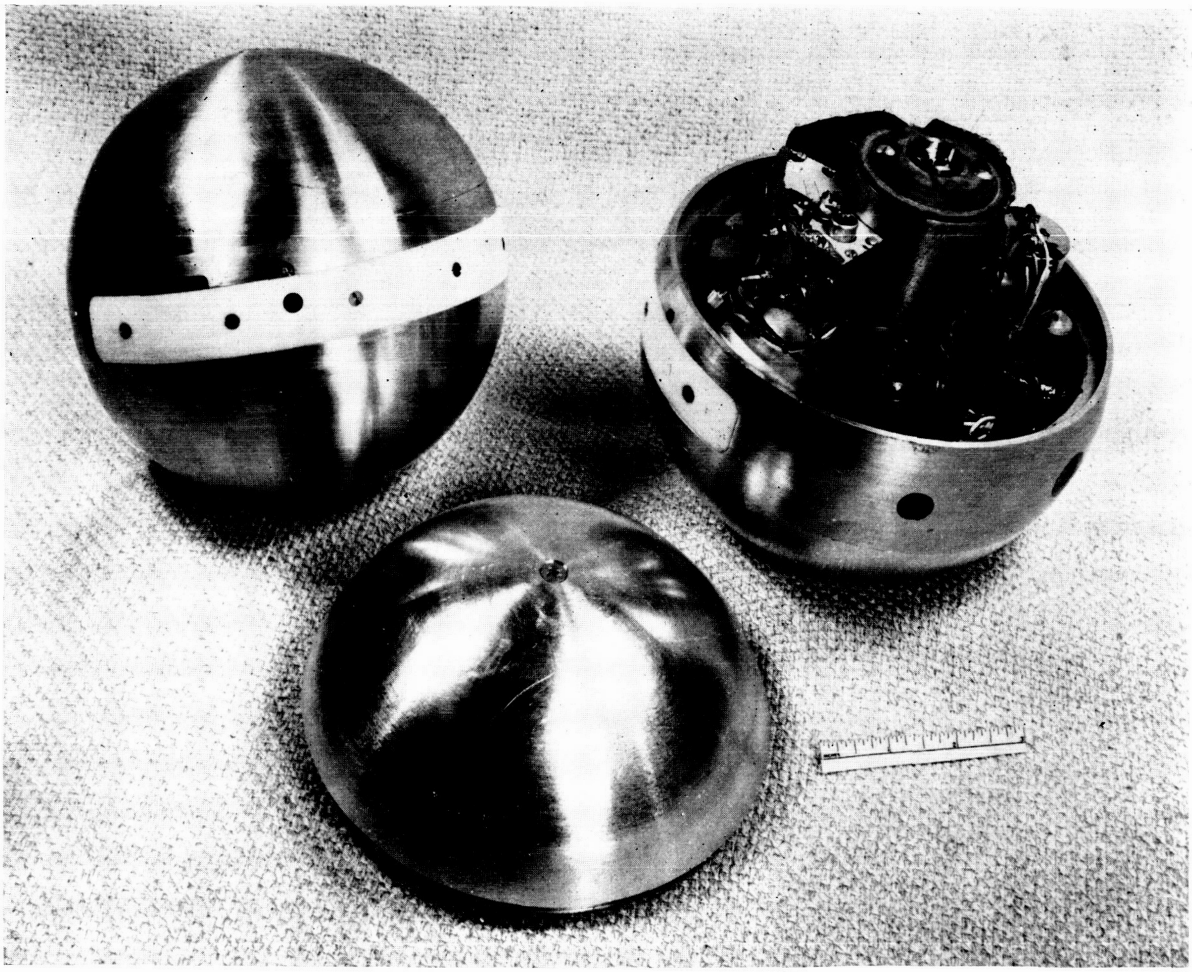

Figure 5.—Seven-inch diameter falling sphere (active, rigid). Left sphere, fully assembled, shows telemetering antenna slot. Open sphere on right shows built-in accelerometer.

Above the 120-km level, the cross section over mass ratio of the sphere is too small to detect any deviations from free fall; at low altitudes there is usually a region where the velocity of the sphere approaches a Mach number regime in which C_D is not known accurately enough and where horizontal winds affect the fall of the inflatable sphere. This depends largely on the type of sphere used, but in general density data have been obtained down to 40 km with inflatable passive spheres and down to 20 km with rigid, active spheres.

The advantage of this technique is that for the active sphere the ground instrumentation is exceedingly simple (one telemetering receiver and recorder) and the flight instrumentation is quite compact, although a high degree of perfection and engineering skill is required to manufacture the spheres and accelerometers. With the passive sphere the costs are greatly reduced, but the ejection and inflation mechanisms are of critical importance and high precision tracking radar must be available. Also, the fall velocity of the inflatable sphere is near the speed of sound in the vicinity of 70 km. Errors may be introduced at this altitude by insufficient knowledge of C_D which changes rapidly with fall velocity near $M = 1$. The drag on the inflatable sphere could also be greatly affected by imperfect inflations and by strong horizontal winds. These problems, of course, do not exist with the active, rigid sphere.

Pitot-Static Tube

A variety of techniques exist to perform *in situ* pressure measurements from rocket vehicles. These techniques are always based on the premise that ambient conditions of pressure, density, or temperature can be derived from the direct pressure measurements carried out on board the vehicle by applying aerodynamic theories which relate the measured pressure to the ambient parameters. The accuracy of the derived ambient pressure, density, and temperature thus depends not only on the precision of the pressure measurement itself, but also on the validity and applicability of these aerodynamic theories. This applicability is generally ensured by keeping such rocket performance parameters as velocity and angle of attack within tolerable limits during the time of measurement. Effects on the pressure measurement by gases carried along with the sounding rocket must be carefully avoided.

In general, the pressure measurement is performed at at least two aerodynamically different locations along the surface of a pitot-static tube carried at the tip of the rocket (fig. 6). Pressure sensors are usually placed in chambers which are exposed to the air flow by means of orifices in the skin of the rocket. In one chamber the stagnation pressure (P_i) at the tip of the pitot tube is measured, and in a second chamber a measurement of static pressure (P_s) along

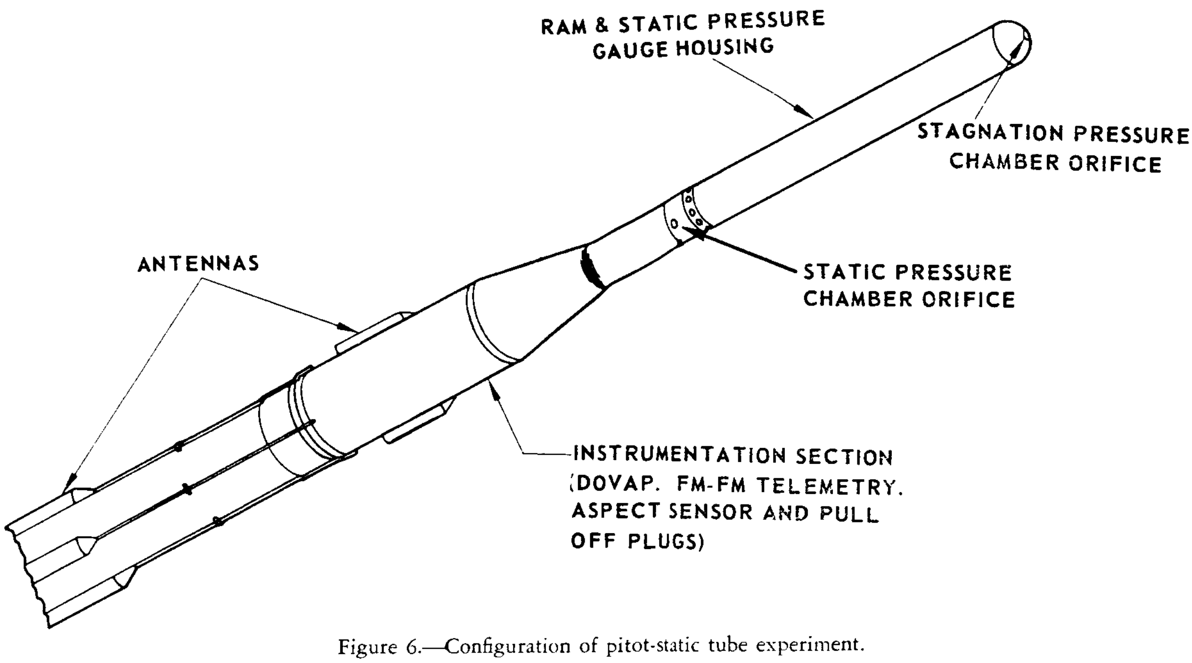

Figure 6.—Configuration of pitot-static tube experiment.

the wall of the same tube is made, several calibers to the rear of the stagnation point.

Aerodynamic tests of this configuration show that the pressure measured at this point is equal to ambient pressure. Additional chambers may be provided for redundancy. As a pressure sensor each chamber consists of a radioactive ionization source and a multi-range electrometer which measures the pressure sensitive ion current. The current, calibrated as a function of chamber pressure and susceptible to measurement in the altitude range of about 40-120 km, is telemetered to the ground. This technique which has been developed in its present state by J. J. Horvath et. al. (ref. 16) is based on pressure measurements originally developed by Spencer (ref. 17) and LaGow (ref. 18). During various developmental stages, about 10-20 successful flights of this basic technique have been carried out since 1953 (ref. 18, 19, 20).

Ambient density ρ is derived from the interpretation of the basic Pitot static tube equation (Rayleigh Equation) and from the equation of state:

$$\rho \sim \frac{P_i}{V^2} \qquad (2)$$

This proportionality holds essentially over a Mach number range of $3.5 < M < 7.5$; V being the tangential velocity of the rocket which must be determined by accurately tracking the rocket. This is usually done with a Doppler velocity tracking system.

The above proportionality relating impact pressure to ambient density as well as the ability to measure ambient pressure directly at the side of the Pitot tube hold only in the region of continuous flow where the mean free path between molecule collisions is small compared to the dimensions of the sensor. At higher altitudes, in the free molecular flow region, where the mean free path becomes larger than the sensor dimensions, these methods break down. The transition between continuous and free molecular flow occurs near the upper boundary of the mesosphere at about 90 km. Above that altitude the above proportion is replaced by the following expression, which relates the ambient density ρ to the impact pressure P_i in the region of continuous flow:

$$\rho = \frac{P_i}{KV} \cos \alpha \qquad (3)$$

where α is the angle of attack of the rocket and K is a function of the temperature in the chamber and of the molecular mass. With present techniques this type of density measurement can be performed up to 120 km. Ambient pressure can only be measured directly in the continuous flow region (up to 90 km).

Complete profiles of density (ρ), pressure (P) and temperature (T) can be derived from each one of the three experiments described above, although the primarily determined parameter is pressure in the Pitot tube experiment, density in the sphere experiment, and temperature in the grenade experiment. The three parameters are related through two well-known relationships which are derived from the equation of state and from the hydrostatic equation:

$$-\frac{dP}{dh} = P(h)\,\frac{Mg(h)}{RT(h)} = \rho g(h) \qquad (4)$$

where g is the acceleration of gravity; M is the molecular mass (usually assumed constant up to 90 km) and R is the universal gas constant. Because these three parameters are so interrelated the need for a comparative measurement between the three experiments is obvious. A nearly simultaneous experiment involving the grenade, pitot tube and falling sphere techniques was conducted on June 6, 1962, and the results are discussed below.

A summary of these four, most successful techniques for the measurement of temperature, pressure, density, and wind with an indication of their altitude range is given in figure 7.

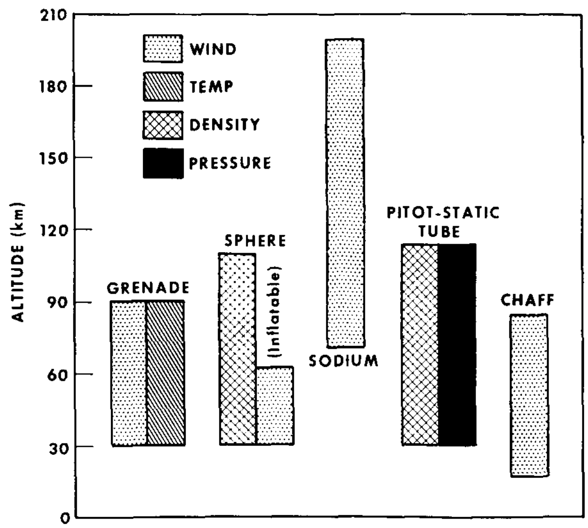

Figure 7.—Theoretical altitude range of experiments measuring winds, temperature, pressure, and density in the mesosphere.

In comparison to the number of pressure, density, temperature, and wind soundings the number of rocket flights measuring composition of the mesosphere has been very small. At higher altitudes, in the thermosphere, mass spectrometers have been successfully used. These measurements, however, are not readily applicable at lower altitudes. Below 100 km two types of composition measurement are of greatest interest: the determination of the gross molecular mass; and of the concentration of trace constituents such as ozone, water vapor, and atomic oxygen important to the radiative equilibrium of this region. Water vapor measurements with balloons already become very difficult in the upper troposphere and in the stratosphere, and at this time cannot be carried out at higher altitudes. Ozone content has been measured in occasional rocket flights by observing the increase in the intensity of solar radiation in the near ultraviolet with altitude. Originally this involved elaborate spectrographs carried aboard Aerobee rockets where the films had to be recovered (ref. 21). More recently attempts have been made to simplify this technique and adapting it to smaller rockets by measuring the absorption of sunlight by ozone in several narrow parts of the 2700- to 3300-Å regions sensing the light intensities with phototubes. The phototube signals are telemetered to the ground, thus eliminating recovery (ref. 22). Ozone measurements in the upper stratosphere and mesosphere would be highly desirable during the polar night, but, so far, all rocket-borne techniques are based on the absorption of sunlight. Research is presently directed toward the development of rocket-borne ozone sondes which are independent of sunlight.

A technique for measuring composition of the atmospheric constituents in the 70- to 90-km region is the collection of air samples by means of evacuated steel bottles. The sealed bottles are carried to the desired altitude, opened for about 5 sec, and then sealed again. About six successful samplings were carried out in the United States (ref. 23) during 1953-1956, and some in the Soviet Union (ref. 24). After recovery of the bottles the contents were chemically analyzed. Only the inert gases were susceptible to analysis; thus, the ratios of helium, neon, and argon to nitrogen were determined. This measurement permits the determination of the altitude level above which the gross molecular mass begins to decrease due to gravitational separation of the lighter constituents from the heavier ones.

A different technique has been used recently to obtain samples of particulate matter from the 70-90 km region (ref. 25). In this experiment, particles of sizes in the order of 0.1 micron were collected, recovered, and analyzed to determine the nature and composition of noctilucent clouds, one of the most outstanding mesospheric phenomena at high latitudes.

PRESENT ROCKET SOUNDING PROGRAMS

Being geophysical measurements, atmospheric soundings should ideally be conducted as worldwide programs at all geographical locations and seasons. A concerted effort during the International Geophysical Year (IGY) brought about the first measurements from which geographical variations of the structure of the mesosphere could be derived. In fact, the four methods mentioned—sodium release, grenade, pitot-static tube, and falling sphere—reached their stage of full development during that period, and their success during the IGY is the reason why the measurements of pressure, density, temperature, and winds in the 50- to 90-km region still evolve around these four techniques.

Much progress has been made since IGY in extending the geographical coverage of the soundings. The world map (fig. 8) indicates the sites at which rocket soundings employing the techniques described were conducted during recent years. Many of these soundings were internationally coordinated as a first attempt toward a synoptic program. It is hoped that a further realization of synoptic soundings, as well as an increase in the number of launching sites will be accomplished during the forthcoming International Quiet Sun Year (IQSY).

In the United States, a program directed by the Goddard Space Flight Center of NASA has been in progress since 1959. This program is oriented toward the following objectives:

1. The exploration of the mesosphere during all seasons of the year over Wallops Island, Virginia (38°N), a typical midlatitude site.
2. A direct comparison of the four techniques described and a mutual "calibration" of these techniques by means of simultaneous soundings. Such a comparison was accomplished on June 6, 1962, at Wallops Island, Virginia.
3. The observation of continuous wind profiles throughout the lower atmosphere by combining radiosonde balloons, small meteorological rocket sondes, grenade, and sodium experiments. On

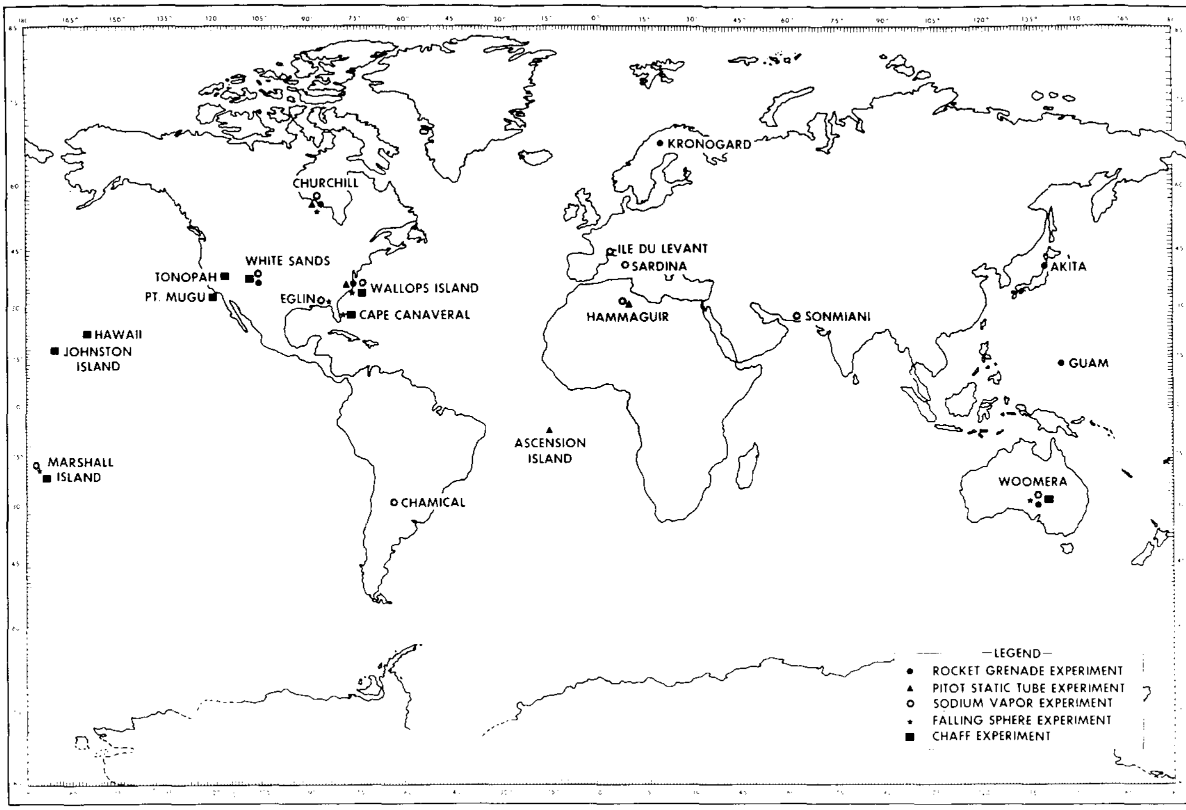

Figure 8.—Map of locations from which rocket soundings in the mesosphere have been conducted during and since IGY. The type of experiment performed is indicated at each station.

four occasions during 1961-1963, wind profiles from the ground up to above 150 km were obtained. The various circulation regimes in the various sections of the atmosphere were very well demonstrated in these experiments.

4. To conduct simultaneous soundings at mid-latitudes (Wallops Island, 38°N), in the sub-arctic (Churchill, Canada, 59°N) and in the tropics (Atlantic, 7°S). Simultaneous launchings at Churchill and Wallops Island started in December 1962 and it is hoped a tropical site can be added by late 1963.

The program started with two sodium soundings each in August and November 1959 and in May and December 1960 at Wallops Island. One successful grenade sounding was conducted in June 1960 at the same site. Between 1961 and 1963 a total of 22 successful grenade experiments were launched at Wallops Island and five at Churchill during December 1962, and February and March 1963. In the same period, 16 sodium releases were made at Wallops Island, 13 of which were simultaneous with grenade experiments.

During November 1962 an international series of sodium releases coordinated with various sites around the world (fig. 8) was conducted. On several other occasions coordinated sodium releases were made between Wallops Island and Italy and between Wallops Island, France, and North Africa. One sphere experiment was conducted in 1961 and another simultaneously with grenade pitot tube and sodium experiments at Wallops Island on June 6, 1962. On December 1, 1962, a simultaneous pitot tube and grenade experiment was successfully launched at Wallops Island. Four grenade experiments were conducted during July and August 1963 in northern Sweden, two of them during the display of noctilucent clouds. These four experiments were carried out through the cooperation of the Swedish Space Committee and NASA.

A summary of all firings at Wallops Island and their range of data recovery is shown in figure 9.

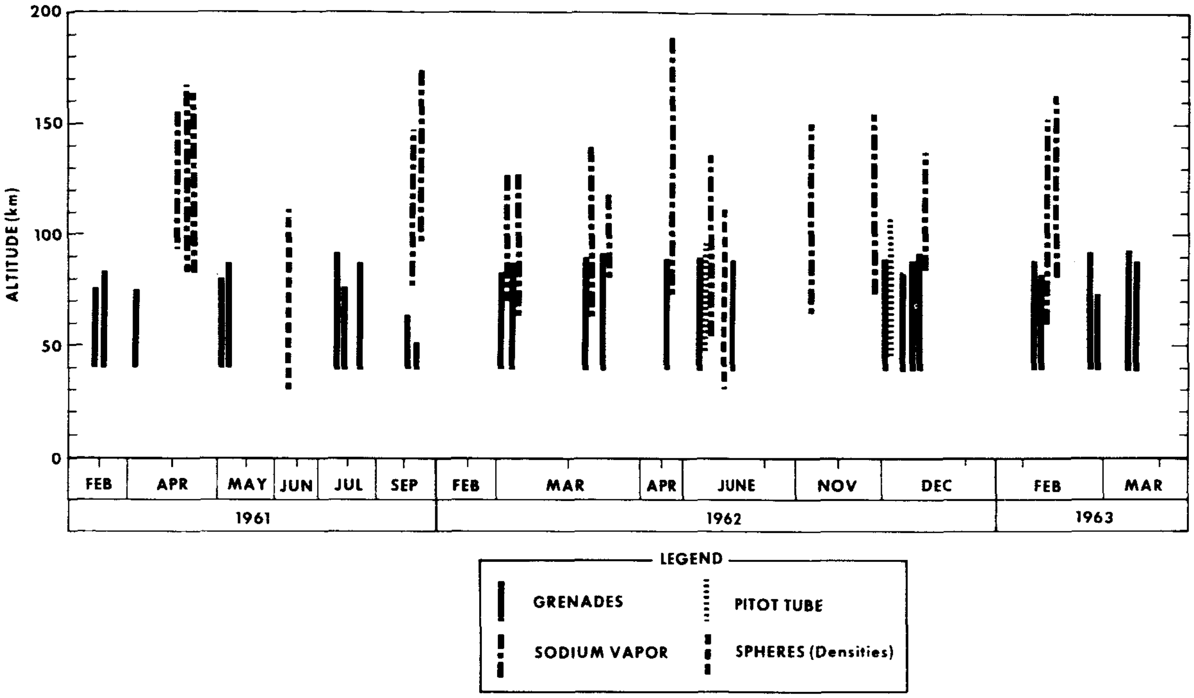

Figure 9.—Summary of mesosphere rocket soundings performed at Wallops Island, 1961 through 1963, showing time of launching, type of experiment, and approximate range of actual data recovery for each sounding.

RESULTS OF RECENT ROCKET SOUNDINGS

The following features of the mesosphere had been derived as a result of earlier sounding programs during IGY:

1. A large variation of the temperature profile in the 60- to 90-km region between high and low latitudes or between summer and winter at Churchill with large and multiple temperature maxima in the winter mesosphere at Churchill.
2. The existence of an extremely strong cyclonic circulation up to 80 km over the entire winter hemisphere, which extends, though greatly diminished, into the equatorial zone. This vortex is replaced by anticyclonic circulation of lesser intensity for the summer hemisphere, again reaching far into the tropics.
3. A breakdown of the wintertime circulation up to 70 km at Churchill where meridional circulation in the stratosphere and mesosphere preceded the occurrence of a typical explosive warming at lower levels.
4. A systematic seasonal variation of pressure, temperature, and density at high latitudes where variations by a factor of two in density were observed between summer and winter at 60 km.

Results from the recent soundings confirm the behavior of the temperature and wind structure previously derived from only 10 soundings at Churchill during IGY (ref. 1, 2). This picture holds generally also for a typical midlatitude site such as Wallops Island (38° N). Average temperatures for summer and winter over Wallops Island and their variability from day to day are shown in figure 10. The averages were derived from five soundings in June 1962 and July 1960 and 1961, and from nine soundings in December 1962, February 1961 and 1963, and March 1962 and 1963. Although the temperature difference between winter and summer above 60 km is not as large as previously observed at Churchill, the temperatures at 38° N are still considerably higher during the winter months than during summer. The temperature variations between individual soundings are also much larger in winter than in summer. The maximum variation at 70 km during summer covers a range of about 23° K, while in winter the variation at the same altitude amounts to 39° K. At about 60 to 65 km summer and winter temperatures coincide; this has also been observed at Churchill dur-

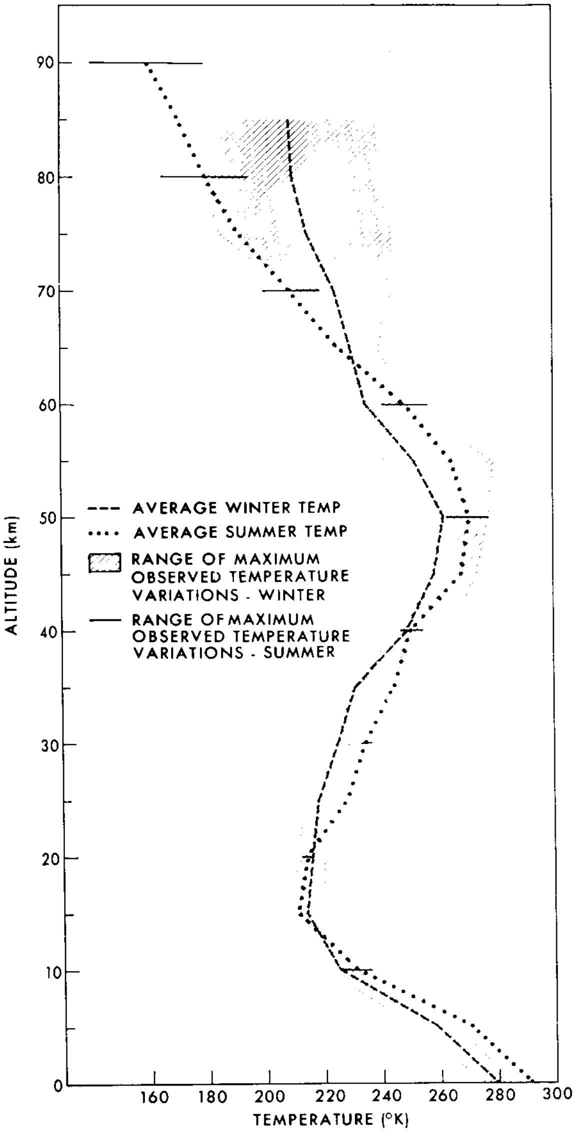

Figure 10.—Average profiles of temperature versus altitude for winter and summer over Wallops Island (38° N). Summer average was obtained from 5 soundings 1961 through 1963, and Winter average from 9 soundings 1961 through 1963. Maximum variation in temperature between soundings is indicated by shading for winter and by horizontal bars for summer soundings.

ing IGY. At the 50-km level summer average temperatures at Wallops Island are about 15° K higher than winter temperatures. Individual temperature and wind profiles for the Wallops Island soundings up to June 1962 have been published previously (ref. 26). Results from four soundings in April and May indicate that temperatures during these transition months fall between the summer and winter profiles above 65 km, but that in the upper stratosphere, at the 50 km level and below, springtime temperatures are usually about 10° higher than summer temperatures.

These temperature variations have a profound influence on the seasonal variations of density with altitude. Figures 11 and 12 show deviations of observed densities from the 1962 United States Standard Atmosphere (ref. 27) for each individual sounding as a function of altitude. The magnitude of this density variation at Wallops Island is not as large as previously observed at Churchill (ref. 28), but winter densities throughout the 30- to 80-km region are still appreciably lower than summer densities. Maximum seasonal variation occurs between 60-80 km where winter densities are lower than summer densities by an average ratio of about 0.8. During IGY at Churchill, this ratio was about 0.5. Supplements to the United States Standard Atmosphere are now in preparation to reflect these seasonal and latitudinal changes (ref. 29). It is interesting to note that the two profiles for February 1961 are closer to a summer than winter condition. This is attributed to a very warm stratosphere which prevailed at that time at altitudes below 40 km. These high tempera-

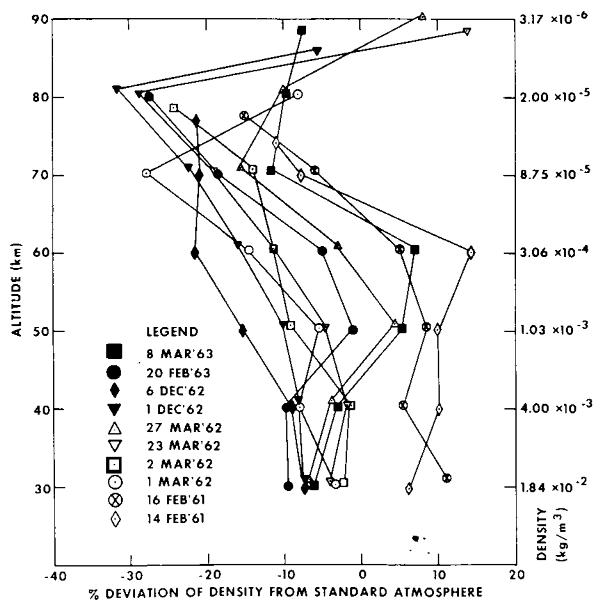

Figure 11.—Winter densities as a function of altitude derived from individual temperature soundings obtained with the rocket grenade experiment over Wallops Island 38° N). Densities are shown as percent deviation from 1962 U.S. Standard Atmosphere (ref. 27).

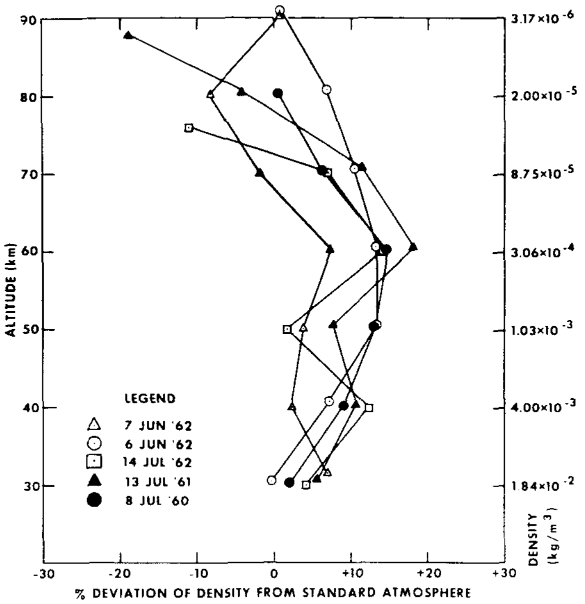

Figure 12.—Summer densities as a function of altitude derived from individual temperatures soundings obtained with the rocket grenade experiment over Wallops Island (38° N). Densities are shown as percent deviation from 1962 U.S. Standard Atmosphere (ref. 27).

tures, at lower levels, cause the higher densities throughout the mesosphere.

The wind field again shows the same features as those found in IGY, namely easterly flow in summer and westerly in winter with strong meridional flow during the transitions in February and March. However, an additional feature stands out from the Wallops Island results. (figures 13 and 14). This feature, described as follows, is also obvious from the comparison between grenade and sodium winds in the 60–90 km region which can be made from figure 15.

A sharp and remarkable boundary seems to separate the circulation below 80 km from the circulation in the regions where ionization of the atmosphere and dissosiation of oxygen sets in. This boundary lies near 80 km and seems to suggest that the physical causes which sustain the motions of the atmosphere are quite different in the two regions. As described above, the winds below 80 km conform to the pattern of uniform zonal flow, regularly reversing with season, interrupted only by occasional breakdowns during the spring transition. Above this altitude, however, the flow is no longer uniform and exhibits no regular seasonal pattern. Some features are common, nevertheless, to most of the wind profiles taken above 80 km; namely, the strong, but highly variable winds sandwiched between zones of relative calm resulting in extreme wind shears. Thus far, every sounding conducted has shown these wind shears between 90 and 110 km. Above 120 km greater uniformity seems to return, but samples at these altitudes are too few to derive any definite circulation patterns.

A most interesting and important result of the sounding program at Wallops Island has been the direct comparison of various experiments at various altitude regions. Previously a report (ref. 26) had been made of the rather discouraging disagreement

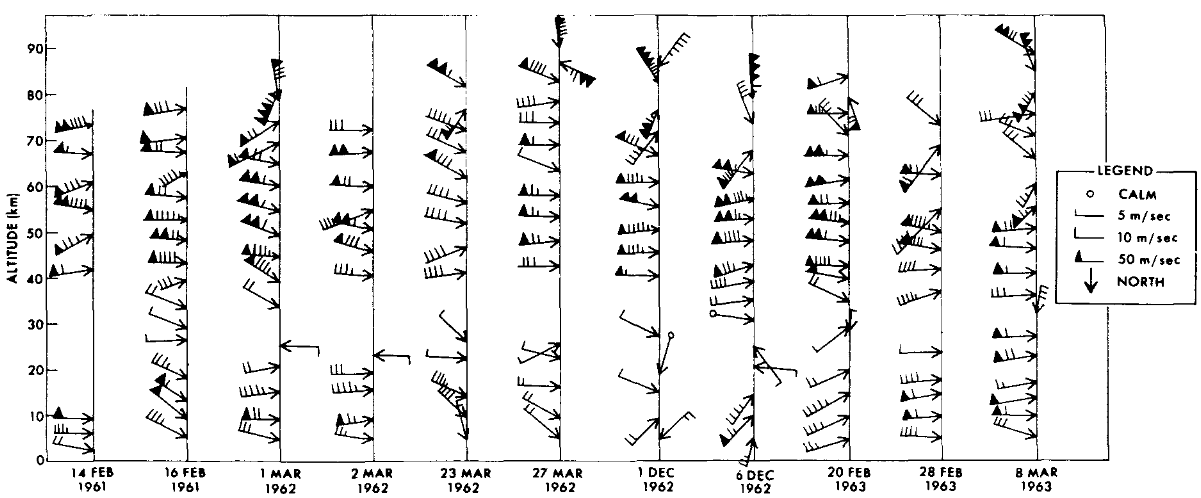

Figure 13.—Winter measurements of wind speed and direction versus altitude as measured by the grenade experiment over Wallops Island. (38° N).

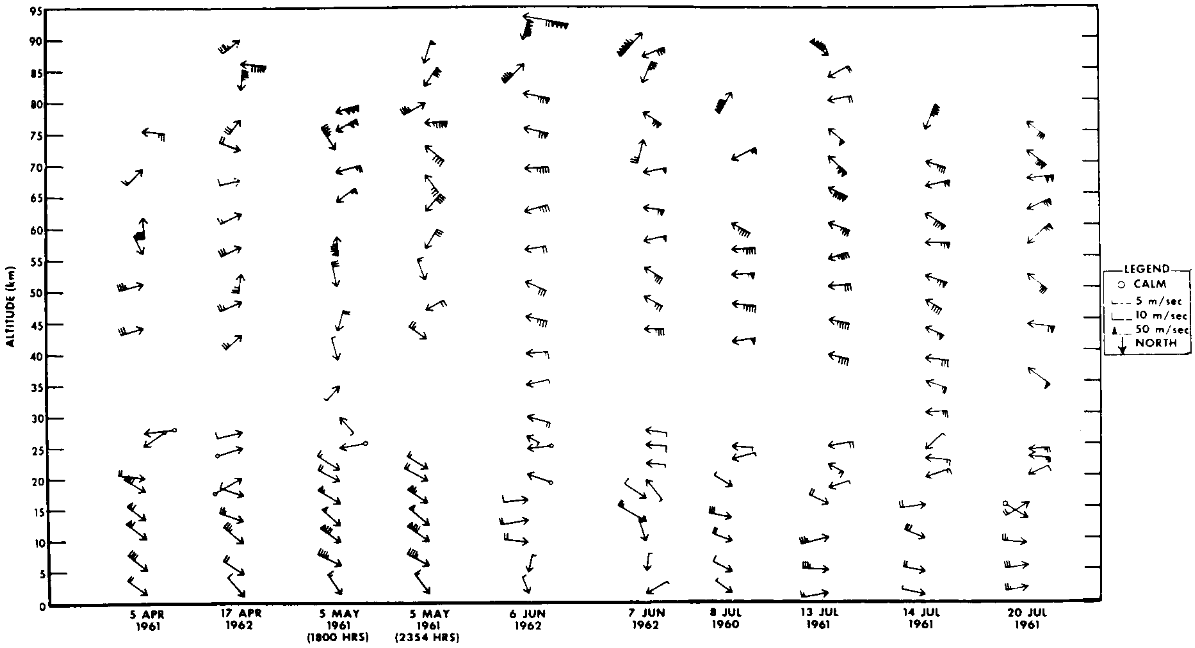

Figure 14.—Summer measurements of wind speeds and direction versus altitude as measured by the grenade experiment over Wallops Island (38° N).

between temperatures measured directly by the thermistor method, used in the small meteorological rockets, and by the grenade method at the 50-km level. From recent results (fig. 16, December 1962), it seems that this discrepancy has been greatly reduced, and in the February and March 1963 comparisons (Figure 17) has all but disappeared. This is attributed to a substantial improvement in the thermistor temperature sensor which is now flown in the HASP rocket at Wallops Island.

A comparison of wind measurements between the grenade method and the various methods used with small meteorological rockets in the 40- to 60-km region, in most cases, shows very good agreement.

Comparisons between the grenade technique which yields average winds in layers of a few kilometers thickness and the sodium experiment yielding a continuous wind profile with altitude show that there is fair agreement in many but not all cases where the flow pattern is still uniform (below 80 km) and where the violent wind shears usually observed at the higher altitudes do not exist. In the shear regions the agreement is generally very poor, obviously because the average winds obtained by the grenade method are not comparable to the rapidly changing instantaneous wind vectors determined by the sodium trails (fig. 15).

A most interesting comparison was conducted between the sphere, grenade, and pitot tube experiments on June 6, 1962. A passive, inflatable falling sphere was carried on the same rocket as the grenade experiment (ref. 14) and a pitot tube experiment was conducted within less than ½ hour. Density profiles resulting from each of the three techniques are shown in figure 18.*

From 30–65 km and at 90 km the agreement between the pitot tube and grenade techniques is quite good (better than 5%); this can be considered within the measurement errors of the two experiments. Between 65 and 85 km, the disagreement is considerably larger: 9% at 70 km and 13% at 80 km. The grenade and sphere methods are in fair agreement up to 75 km; discrepancies there are less than 10%. From 65 to 75 km, grenade densities are about 5% lower than falling sphere densities and about 5 to 10% higher than pitot tube densities. Below 60 km falling sphere densities are generally lower

* The pitot-static tube experiment was conducted by J. J. Horvath and the falling sphere experiment by J. W. Peterson—both of the University of Michigan, Ann Arbor, Michigan. The grenade experiment was performed by Wendell S. Smith of NASA Goddard Space Flight Center, Greenbelt, Maryland. The kind permission of these researchers to use their data for this comparison is gratefully acknowledged.

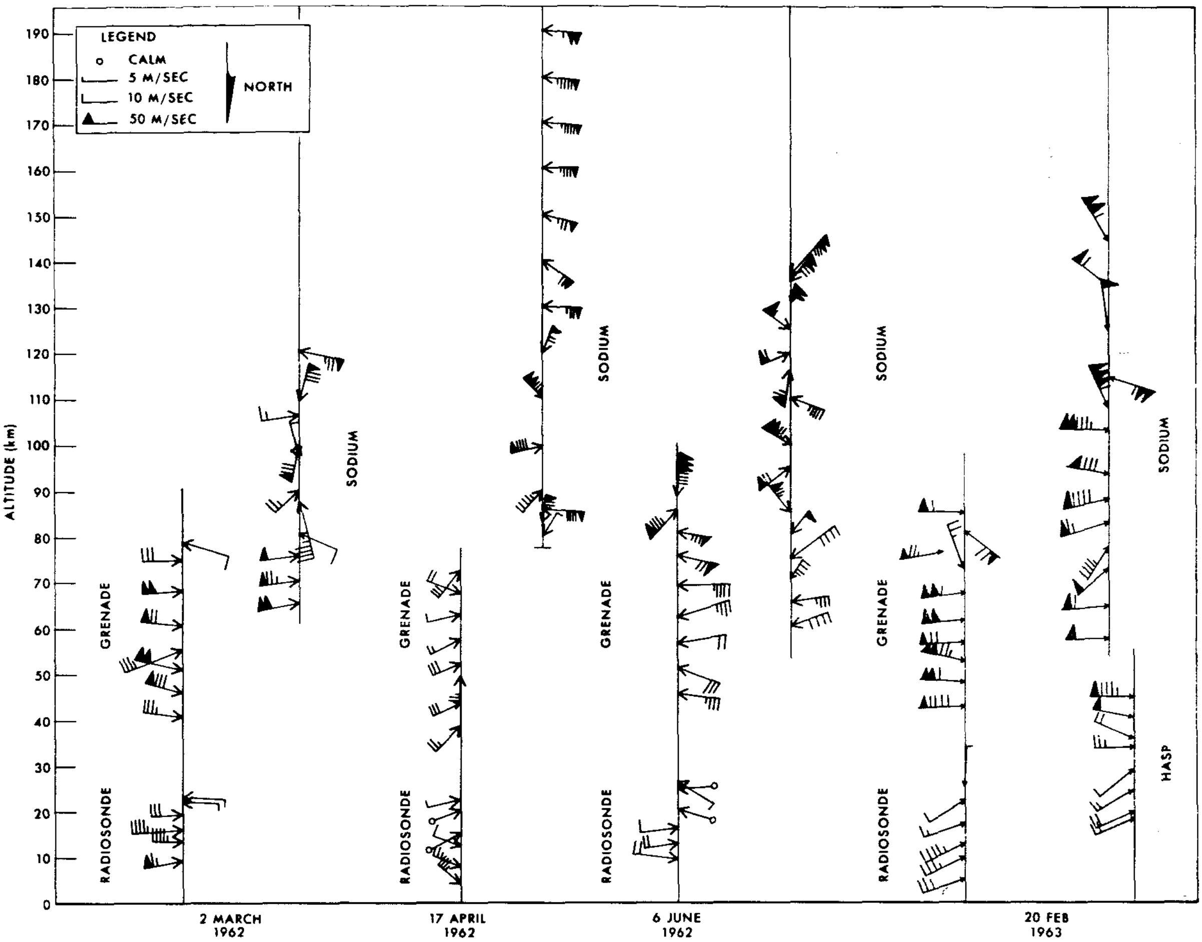

Figure 15.—Wind speed and direction versus altitude as obtained nearly simultaneously with balloon-radiosonde, grenade and sodium techniques over Wallops Island, (38° N) on March 2, 17 April and June 6, 1962, and with balloon radiosonde, grenade, sodium, and rocketsonde (HASP) techniques on February 20, 1963.

that pitot tube and grenade densities. Over the entire altitude range, the pitot tube densities are always lower than the grenade densities indicating the possibility of a systematic error.

The largest discrepancies between falling sphere data and grenade and pitot tube data occur near 85 km, while at 90 km results from all three methods agree remarkably well.

It is possible that the fluctuation in the falling sphere data between 65 and 75 km could be explained by the fact that the sphere passes through the transsonic velocity regime at this altitude range where the drag coefficient (C_D) changes rapidly. In fact, the Mach numbers given for the sphere by Peterson (ref. 14) range from 1.46 at 75 km to 0.63 at 65 km and at 72 km $M = 1$.

Since the passive, inflatable sphere is a relatively recent development difficulties such as those mentioned have not yet been fully evaluated. The conclusions which can be drawn from this comparison must therefore be considered highly preliminary.

A similar comparison was conducted between grenades and pitot tube on December 1, 1962. Preliminary results indicate that the agreement is not as good as on June 6, 1962, but no final conclusions can be drawn until the data analysis is complete.

Finally, results from four simultaneous grenade soundings at Churchill and Wallops Island in December 1962 and February and March 1963 were compared. All four temperature profiles exhibit the same feature; one typical pair of soundings for March 8, 1963 is shown in figure 19. At 90 km, temperatures at the two sites nearly coincide. Tem-

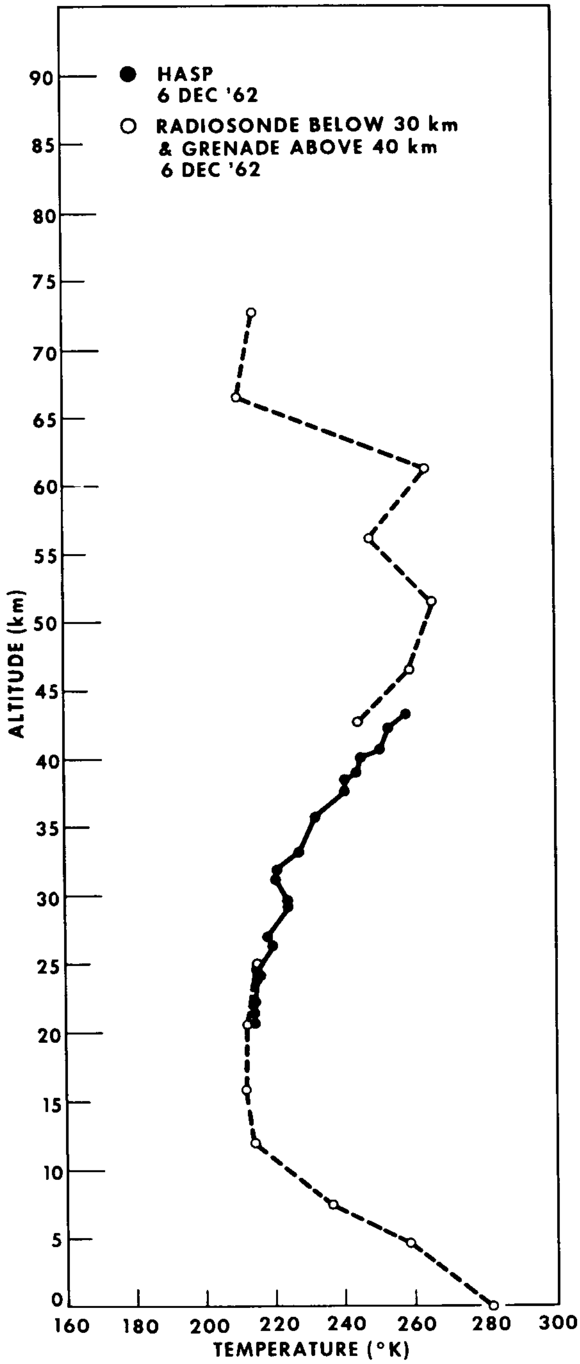

Figure 16.—Comparisons of nearly simultaneous temperature measurements obtained with grenade, rocketsonde (HASP), and radiosonde techniques over Wallops Island December 6, 1962.

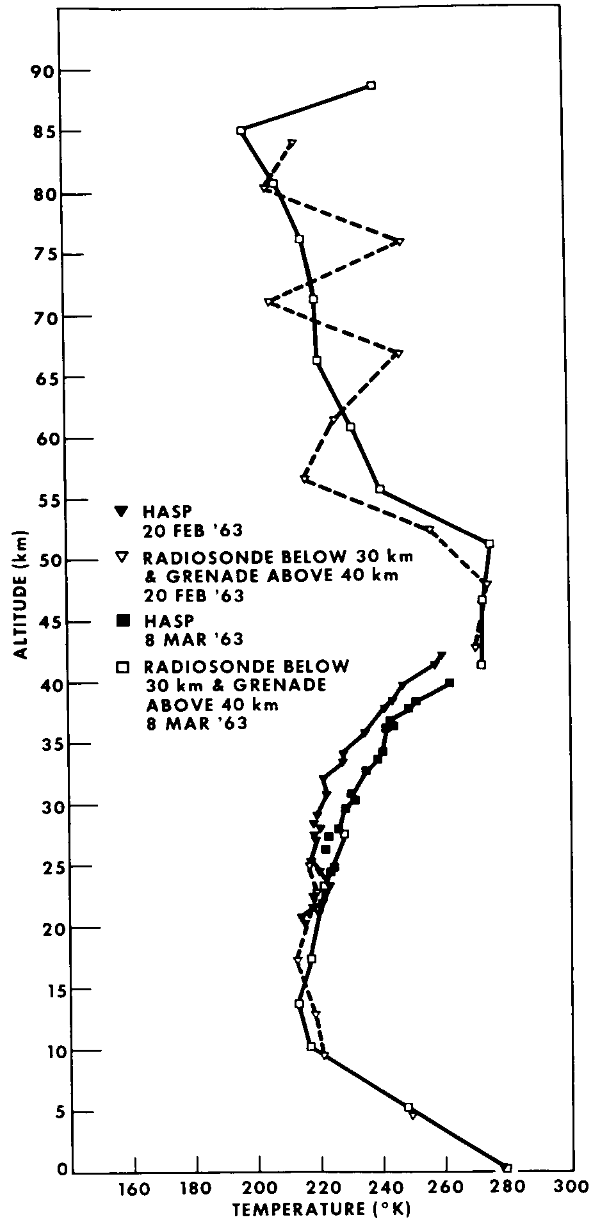

Figure 17.—Comparisons of nearly simultaneous temperature measurements obtained with grenade, meteorological rocketsondes (HASP), and radiosonde techniques over Wallops Island on February 20, 1963 and March 8, 1963.

peratures at Churchill are higher by 10 to 20° K between 55 and 80 km. Around 55 km temperatures are the same at the two locations and below 55 km, Wallops temperatures are appreciably higher (10-20° K). It is assumed that this condition holds throughout the stratosphere although no meteorological rocket (thermistor) data exist for comparison at Churchill and stratospheric temperatures there must be inferred from interpolating between the balloon radiosondes at 20 km and the grenade data at 40 km.

There is, however, a strong variation from day to

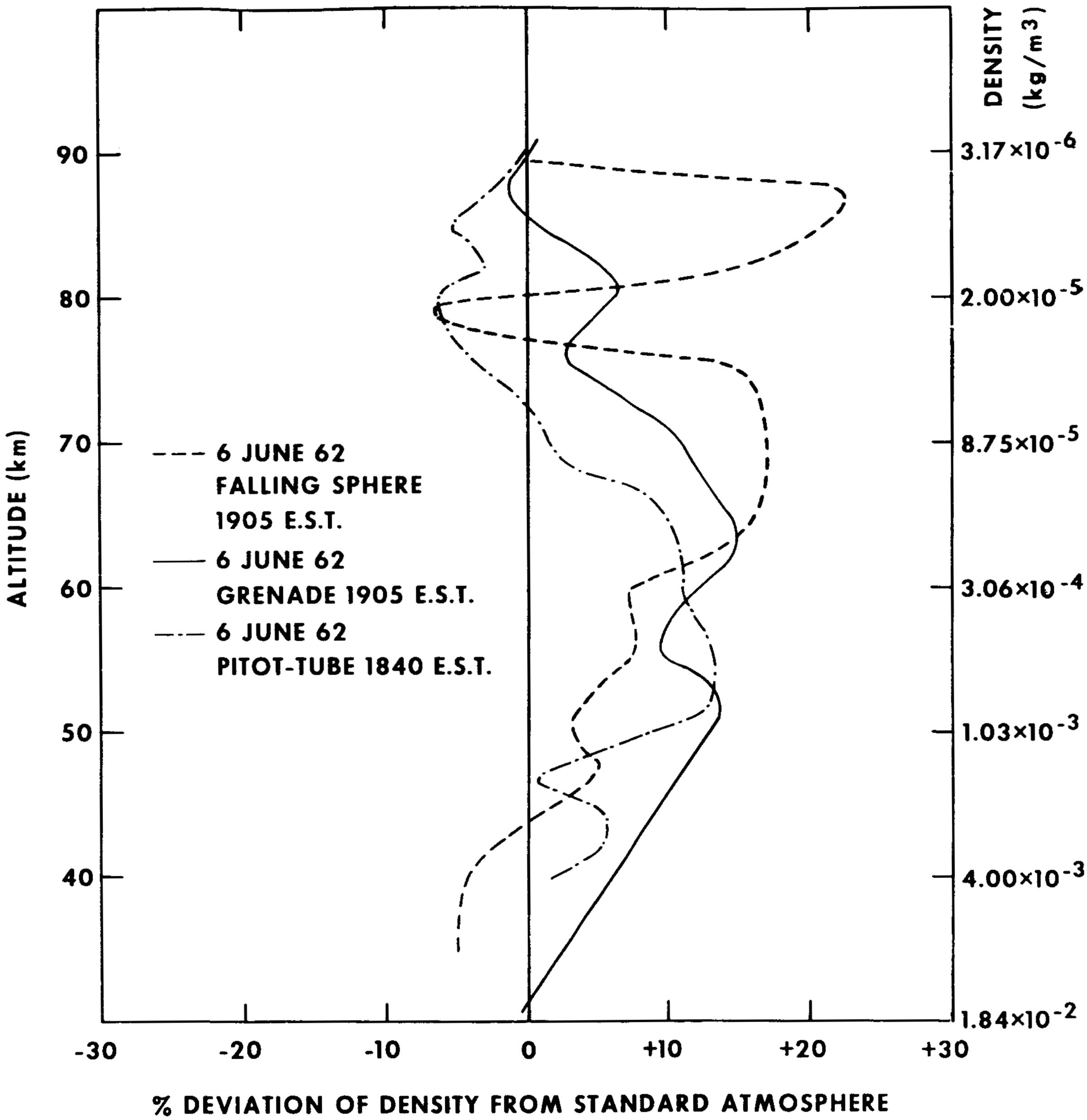

Figure 18.—Comparison of densities obtained nearly simultaneously with the falling sphere, rocket grenade and pitot tube techniques on June 6, 1962, over Wallops Island (38° N). Densities are shown as deviations from 1962 U.S. Standard Atmosphere (ref 27).

day in the temperature profiles at each site that this observation can be made only on individual pairs of simultaneously obtained profiles and does not hold for profiles averaged over several soundings. In general, it may be concluded that the temperature profile between the ground and 90 km becomes more and more isothermal as one progresses from the tropics toward the winter pole.

OUTSTANDING PROBLEMS

The basic techniques used during IGY are still adequate for the measurement of temperature, density, pressure and wind. Because of their long history, their reliability is very high. However, the absolute accuracy of the measurements must be further tested and possibly improved through comparative "calibrations" of the various methods. Depending on the

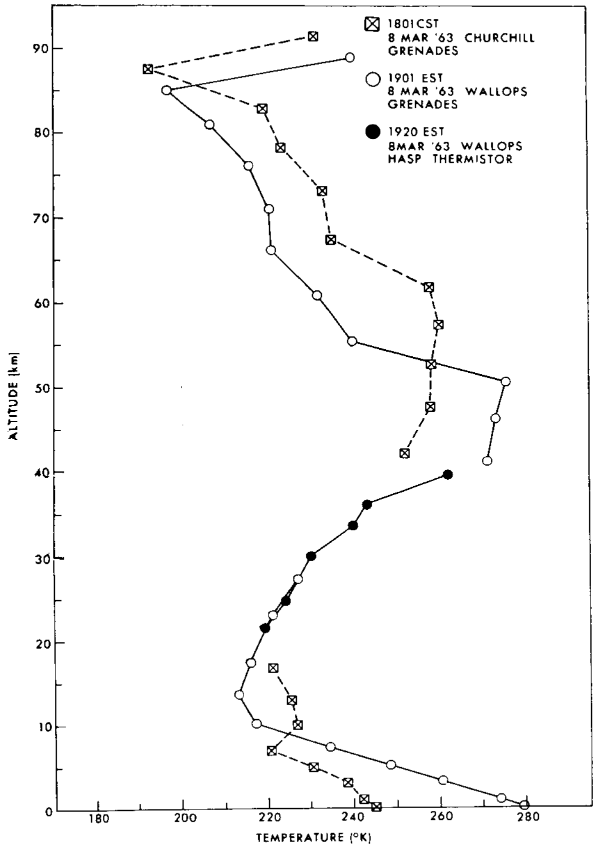

Figure 19.—Temperatures as a function of altitude as obtained by nearly simultaneous rocket grenade soundings over Wallops Island (38° N) and Churchill, Canada (59° N). Radiosonde temperatures at both sites and meteorological rocketsonde temperatures (HASP) for Wallops Island are also shown.

available facilities, one or more of these techniques may be appropriately adapted to launching sites throughout the world. By far the greatest task is to increase the geographic coverage with these soundings by soliciting the cooperation of more individual launch sites all over the globe. For instance, lack of adequate launch facilities has made it impossible, as yet, to obtain structure measurements in the mesosphere during the polar night, which is of foremost importance in answering the question of heating in the mesosphere.

With respect to the physics of the mesosphere, the cause of the high temperatures and their great variability above 60 km during wintertime remains one of the biggest outstanding questions. The entire question of energy exchange between radiation and the potential energy stored in the atmosphere and between potential and kinetic energy should be investigated and more data both at more locations and at more frequent intervals are needed for that purpose.

More synoptic soundings throughout the atmosphere will also enable us to determine the interaction between various circulation regimes in the atmosphere and may possibly lead to a mechanism for the downward propagation of solar-terrestrial relationships.

It is imperative that the technology of composition measurements be improved. A technique must be found which permits the reliable measurement of ozone and atomic oxygen throughout the mesosphere even in the absence of solar illumination.

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ERRATA SHEET A

July 1964

NASA SP-49 Meteorological Observations Above 30 Kilometers

Page 4, left column, second paragraph, lines 3-5:

The sentence "This figure shows that with ... decreases about 0° K" should be "This figure shows that as one ascends through the well-measured troposphere, the temperature decreases about 70° K."

Page 8, Table 1

a) The box for row entitled "Wind" and column entitled "Ground" should read:

Radar
Radar, GMD
Radar, GMD

and each item should be moved down one line.

b) The boxes for row entitled "Density" and columns entitled "Flight" and "Ground" -- the print should be moved down one line.

Page 9

a) Left column

1. First paragraph, line 5: This should read "... which used a DOVAP system with a 4-ft-diameter..."
2. Last paragraph, line 14: "Aeropee" should be "Aerobee."
3. Last paragraph, line 17: This line should be deleted entirely and replaced with "... with a rocket smaller than the Nike-Cajun proposed ..."

b) Right column

1. Last paragraph, line 7: "... ilnstrumentation" should be "... instrumentation..."